LAND USE PLANNING AND DEVELOPMENT SUITABILITY
IN
QUEENSTOWN, NEW ZEALAND

A thesis submitted in partial fulfilment of the requirements for the
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by
Virginia Cunningham

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ABSTRACT

The demand for residential properties in Queenstown is high, but the demand is not matched by the availability of subdivided land and hence there is pressure to develop land which is less geotechnically suitable. It is therefore important that land use planners have an understanding of geological processes and conditions that impose physical constraints to development.

The Wakatipu Basin lies within the Otago Schist belt. It is underlain by pelitic and psammitic greyschist with minor greenschist and mafic schists. The structure and texture of the greyschists control many of the geomorphic features in the Basin, the most notable being the extensive foliation-controlled slope failures. Glacigenic deposits dating from the Waimean and Otiran Glaciations are preserved in parts of the Basin. Post-glacial geology is dominated by lacustrine and fluvio-deltaic sediments deposited when Lake Wakatipu was more extensive and at a higher level than it is at present. Foundation materials in the Queenstown urban area consist mainly of greyschist bedrock, Otiran-aged tills, and fan-delta complexes, with minor deposits of beach gravels, lacustrine silts and sands, and alluvial gravels.

An engineering geological investigation was undertaken to determine the nature and distribution of the geological material in the Wakatipu Basin. The Basin was mapped at a scale of 1:25,000, and the urban area of Queenstown was mapped in more detail at 1:10,000. The maps produced show bedrock and surficial geology, and geomorphology, and as such they are a guide to expected foundation conditions in the area. Limited laboratory testing was undertaken to determine the grainsize distributions of various surficial deposits.

On the basis of the engineering geological investigation, seven geological conditions and processes affecting or potentially affecting the area have been identified. They are stream bank and lake shore erosion, debris deposition, slope movement, weak foundation materials (silts, cohesionless gravels, schist crush zones), topography, flooding, and seismicity.

The identification and evaluation of the physical constraints forms the basis for the compilation of a Development Suitability Map for the Queenstown urban area (1:10,000). By showing the type of constraint present, and the degree of geotechnical limitation it places on development in that area, the map effectively subdivides the map into parcels delineating areas that are more, or less, suitable for residential development.

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CHAPTER ONE: INTRODUCTION

1.1 Background Statement

The township of Queenstown is situated in a naturally formed bay at the head of Lake Wakatipu. Development over the last thirty years has seen the residential area expand rapidly to the east and west along the lower hill slopes bordering the lake and surrounding Frankton Arm, to the extent that the settlement now covers approximately 6.3×10^6 m^2. The demand for residential properties is high, but is not matched by the availability of subdivided land. It is therefore essential that further urban growth be carefully controlled. The whole of the Wakatipu Ward stands to see an estimated 123% growth in population within the next twenty-two years (Constantine Planners Ltd 1993), which wiil see a greater demand to develop land that is less suitable for normal residential subdivision. To effectively control land use and direct development, it is imperative that planners have an understanding of the physical constraints to development.

Engineering geology has a very important role to play in land use planning, and in the assessment of limitations to residential development. This study follows the engineering geological approach of Bell and Pettinga (1984) to identify and delineate those physical processes and conditions that affect, or have the potential to affect, residential development in Queenstown, and to provide a land zoning approach to guide further development. It is intended that this study will assist the Queenstown Lakes District Council and others in directing appropriate land development options by identifying areas that require site-specific geotechnical investigation prior to subdivision approval.

1.2 Thesis Objectives

The principal objectives of this thesis are:

(a) To provide an engineering geological description of the glacial and post-glacial deposits in the Wakatipu Basin at a map scale of 1:25,000 in order to allow evaluation of geotechnical and hydrological properties of materials, and to provide a geological framework within which the detailed study of the Queenstown urban area can be constructed.

(b) To determine the nature and areal extents of the various geological units in the Queenstown urban area at a map scale of 1:10,000.

(c) To identify those physical processes (active and potentially active) and conditions that impose physical constraints on development in Queenstown.

(d) To prepare a suitable land use zoning map that identifies problem areas associated with residential development based on the avoidance or mitigation of the problem areas.

1.3 Description of Study Area

For the purposes of this report, the "Wakatipu Basin" (also referred to as "the Basin") is defined as the low lying area of land bounded by the Ben Lomond, Coronet Peak, Crown and Remarkables Ranges, and Lake Wakatipu (Figure 1). The Queenstown urban area is defined as the built-up area bordering Lake Wakatipu and Frankton Arm and includes the Sunshine Bay, Fernhill, Gorge Road, Frankton Road, Frankton and Kelvin Heights sections.

The basement rocks of the Wakatipu basin are entirely composed of quartzofeldspathic grey- and greenschists of the Haast Schist Group of Suggate (1961) (Figure 2), and have been mapped by Wood (1962) as belonging to chlorite subzones 2, 3 and 4 (after Hutton and Turner 1936, and Turner 1948). There are no known locations of Tertiary rocks within the basin itself, but infaulted remnants of Oligocene marine sediments occur

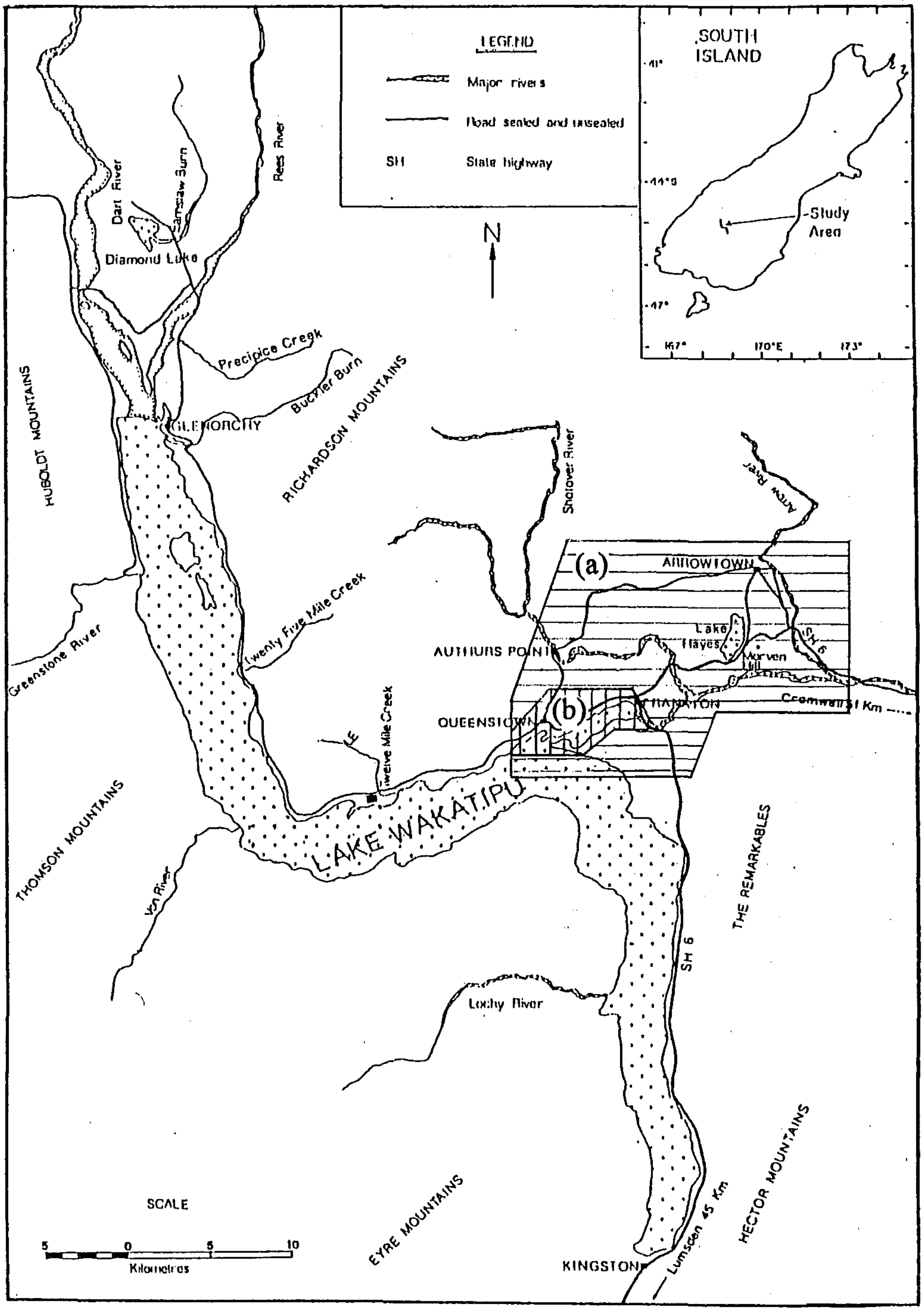

Figure 1: Location of study areas. (a) Wakatipu Basin, mapped at a scale of 1:25,000; (b) The Queenstown Urban Area, mapped at a scale of 1:10,000. (base map from Watts 1988)

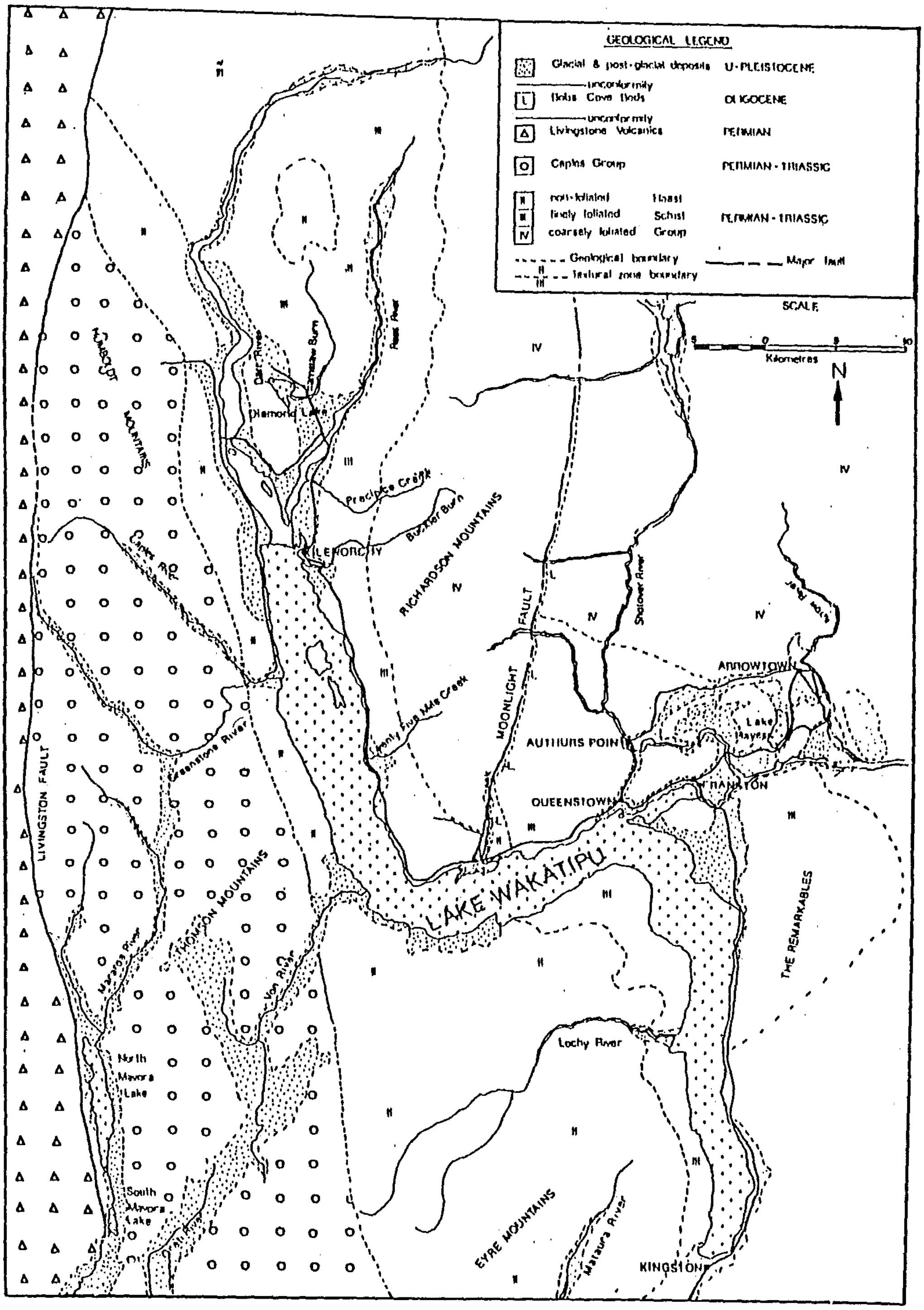

Figure 2: Simplified geological map of the Wakatipu region (from Watts 1988)

along the Moonlight Fault zone, and late Tertiary alluvial sediments and coal measures occur as infaulted slivers along several faults in the Nevis Valley. During the Quaternary, the Wakatipu area was subjected to the same periods of glaciation that affected much of the South Island. Glacial deposits in the area have been assigned to three glaciations - the Waimaungan Glaciation, the Waimean (Penultimate) Glaciation, and the Otiran (Last) Glaciation. Glacial processes have produced a landscape characterised by ice-sculpted bedrock forms, and deposits of tills, kame terraces, and outwash gravels. With the final retreat of the ice, bedrock structure, slope movement and tectonics became the major landscape evolutionary forces.

1.4 Methodology

Following the engineering geology approach of Bell and Pettinga (1984), the following methodology was adopted;

(a) Desk work - a review of existing literature, and stereographic analysis of aerial photographs (a list of the photographs used is given in Appendix A).

(b) Fieldwork - walkover reconnaissance of the Basin region followed by detailed mapping and logging of exposures for both the 1:25,000 map of the Basin, and the 1:10,000 map of the Queenstown urban area. Limited sampling of materials in the urban area.

(c) Laboratory work - analysis of grainsize distribution for samples collected.

(d) Data presentation - compilation of maps: the Engineering Geology of the Wakatipu Basin 1:25,000 (Figure 3, map pocket) and cross sections (Figure 4, map pocket), the Engineering Geology of the Queenstown Urban Area 1:10,000 (Figure 5, map pocket) and cross sections (Figure 6, map pocket), the Engineering Data Sheet 1:10,000 (Figure 7, map pocket), the Development Suitability Map for the Queenstown Urban Area 1:10,000 (Figure 6, map pocket).

1.5 Thesis Format

Following this introduction, Chapter Two discusses the geology and geomorphology of the Wakatipu Basin. Chapter Three outlines the engineering geological investigations of the Queenstown urban area.

Chapter Four describes the major types of physical restraints in the area, gives a background to landuse planning and zonation practices, and discusses the application of engineering geology to land use planning. Chapter Five proposes a physical constraints zonation approach for the Queenstown urban area. Chapter six summarises the project and presents the principal conclusions. The Appendices contain technical data and material not directly relevant to the text.

CHAPTER TWO: THE GEOLOGY AND GEOMORPHOLOGY OF THE WAKATIPU BASIN

2.1 Introduction

The Engineering Geology Map of the Wakatipu Basin (Figure 3, map pocket) was compiled at a scale of 1:25,000. The base map was derived from NZMS 270 Infomap Topographic Series (1:25,000), sheets E41B and D, and F41 A and C (DOSLI 1986). Collection of data involved a review of existing maps and literature, stereographic analysis of aerial photographs, engineering geological field mapping, and discussions with other engineering geologists familiar with the area. In addition, borehole logs were obtained from McNeill Drilling Co. Ltd. for a number of wells drilled in the Basin.

Material descriptions follow Bell and Pettinga (1983) (refer to Appendix B). Mineralogy, texture and structure of the basement rocks were taken largely from Mortimer (1993). Additional information on Quaternary geology was taken from the Surfacial Geology of the Wakatipu Basin map (IGNS in prep).

The geological information is presented within a loose chronological framework, as the aim of this study was to make an engineering geological assessment of materials, rather than to construct a detailed chronology. The inherent complex nature of glacial deposits (especially when dealing with multiple periods of advance and retreat), and the sparse nature of preserved deposits and reliably dated sequences within the Basin, has necessitated the loose grouping of the younger glacigenic deposits together.

2.2 Pre-Quaternary Geology

2.2.1 The Otago Schist

The basement rocks of the Wakatipu Basin consist entirely of schists of the Otago Schist (part of the Haast Schist Metamorphic Belt), straddling the Caples and Torlesse tectonostratigraphic terranes (Figure 9).

The non-schistose Torlesse Terrane rocks to the north of the Otago Schist consist predominantly of marine and deltaic quartzofeldspathic sandstones and argillite, with minor conglomerate, chert, volcanics and limestone. Fossils present within the units range from Permian to Late Triassic in age (Mortimer 1993). To the south of Lake Wakatipu, the non-schistose part of the Caples Terrane consists of Permian age, marine, grey-green volcaniclastic sandstones, siltstones and argillite with subordinate conglomerate, chert volcanics and limestone (Mortimer 1993). Green and purple clasts of well indurated slightly metamorphosed sandstone (greywacke) and conglomerate commonly found within Quaternary and Recent deposits in the Wakatipu Basin are interpreted as being derived from Caples Terrane rocks to the west and northwest of Lake Wakatipu.

Within the Otago Schist Belt, the rocks of both terranes grade from metasediments to strongly foliated schists (TZ II - III & IV) towards the centre of the Belt (Figure 10). The boundaries of the Otago Schist are defined as the I-IIA isotect, which marks the first appearance of foliation in the metasandstone lithologies (Mortimer 1993). Originally interpreted as a feature of the New Zealand Geosyncline, the current thinking on the origin of the Otago Schist is that it is the result of the collision between the Caples and Torlesse terranes which gave rise to metamorphism during the early Jurassic and persisting into the mid Cretaceous (Mortimer 1993).

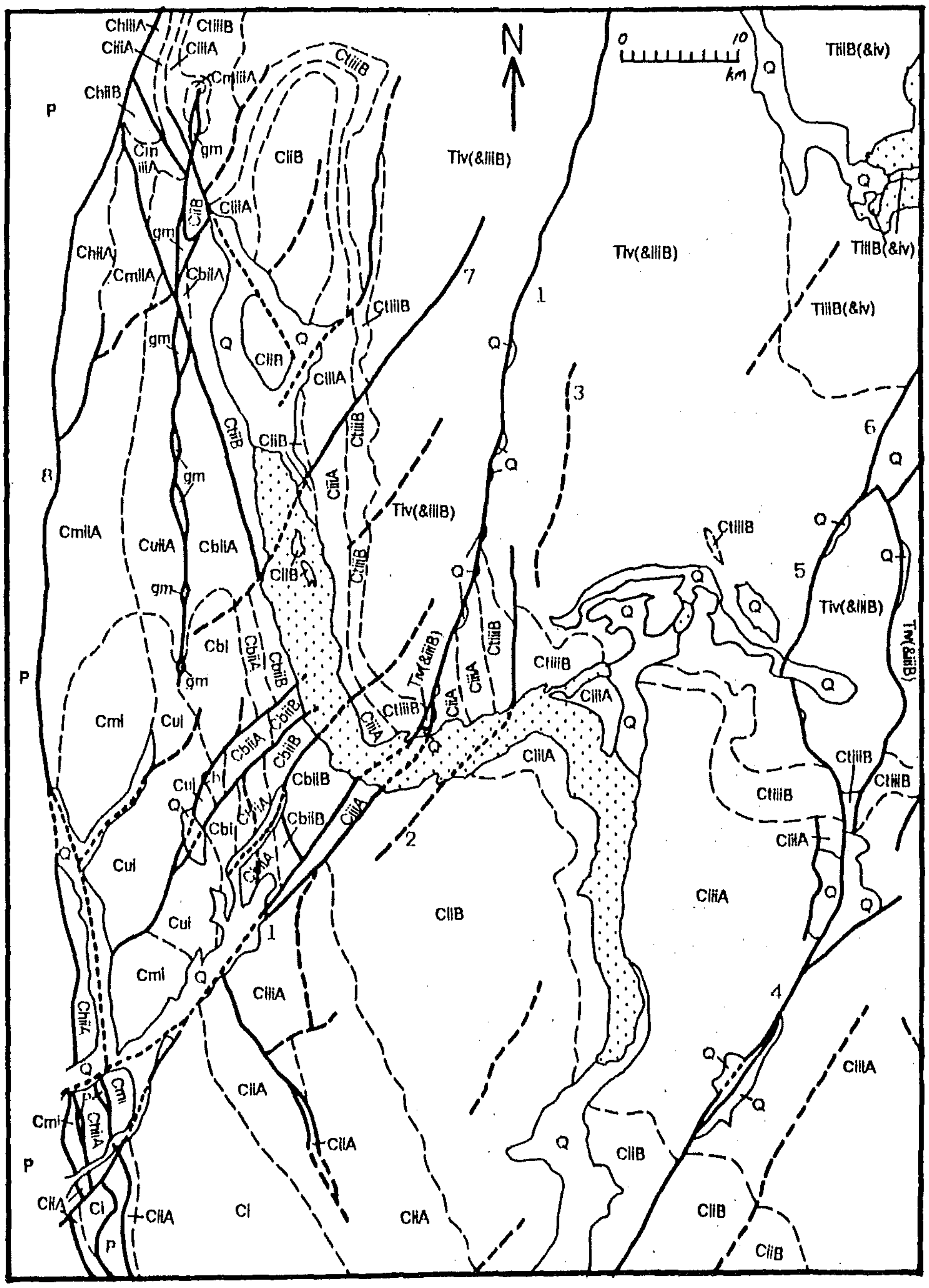

Figure 9: Distribution of the Caples Terrane, Torlesse Terrane and the Otago Schist. Major faults: 1) Moonlight Fault Zone, 2) Two Mile Creek Fault, 3) Shotover Fault, 4) Nevis Fault, 5) Northwest Cardrona Fault, 6) Cardrona Fault, 7) Buckler Fault, 8) Livingston Fault (explanation overpage)

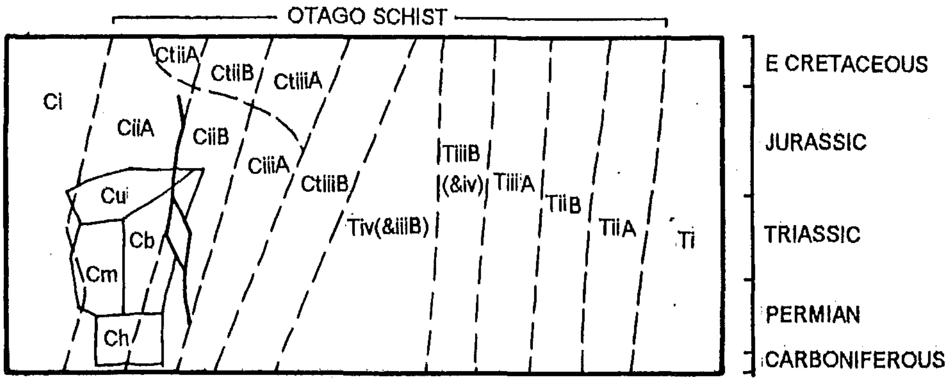

Figure 10: Schematic cross section through the Caples Terrane, Torlesse Terrane, and the Otago Schist.

Key to Figures 9 and 10

C	Caples Terrane, includes:
Ch	Harris Saddle Formation & Westburn Semischist
Cm	Momus Sandstone & Mount Campbell Formation
Cb	Bold Peak Formation
Cu	Upper Peak, Kays Creek & Cosmos Formations
T	Torlesse Terrane
CT	undifferentiated Calples or Torlesse Terrane
gm	Greenschist Melange
P	undifferentiated Matai Terrane and Western Province igneous rocks
Q	late Cretaceous to Quaternary sediments

Textural subzones of the chlorite zone

Zone	Description
i	Indurated, nonfoliated medium grained sandstone
iiA	Slightly foliated metasandstone with widely spaced cleavage
iiB	Penetratively and well foliated semischist
iiiA	Strongly foliated schist with segragation laminae 1-10mm long
iiiB	As for iiiA, but segregation laminae >10mm and <2mm thick
iv	As for iiiA, but segragation laminae >2mm thick

geological contact

fault

isotect

In the Wakatipu Basin region, the schist falls within the chlorite zone of the Greenschist metamorphic facies (Mortimer 1993). Lithology is dominated by psammitic and pelitic greyschist, with minor bands of greenschist, and rare metachert, marble, and ultramafic schist (Turnbull and Forsyth 1988, Mortimer 1993). Structure is characterised by at least two generations of foliation, and micro-, meso-, and macroscopic folds, interpreted by a number of authors (for example, Barry 1966, Rosenstreich 1984, Cox 1985, Ellery 1987) to be the result of several broad phases of metamorphic and post-metamorphic deformation. The mineralogy, texture and structure of the Otago Schist has been studied in detail by a number of authors, most of whom are listed by Mortimer (1993).

2.2.2 Tertiary Sediments

No Tertiary-aged sediments are known to have been preserved in the Wakatipu Basin. Uplift and erosion during the Late Tertiary and Pleistocene has stripped away most of the original cover, leaving only small remnants that have been preserved as sedimentary inliers along major faults outside the study area (Figure 1).

Isolated remnants of early-mid Oligocene marine sediments are preserved along the Moonlight Fault zone to the west and northwest of Queenstown (Turnbull et al 1975, Turnbull and Forsyth 1988). Late Oligocene to early Pleistocene lacustrine and fluvial sediments of the Manuherikia Group are preserved to the east as inliers along the Nevis Fault Zone, and in the Cromwell Basin (Wood 1962, Turnbull and Forsyth 1988). These Tertiary sediments are interpreted as having been deposited during a marine transgression caused by late Cretaceous to Oligocene subsidence at a continent-ocean rifted margin (Mortimer 1993).

2.2.3 Regional Structure

The regional tectonic structure is dominated by Cretaceous northeast-trending normal faults (Figure 9), which have been reactivated during the late Cenozoic under a compressional tectonic regime, forming a series of fault-bounded mountain ranges and basins in the Central Otago region (Mortimer 1993). Two major active fault systems lie just outside the study area, both of which have undergone repeated movement during the late Quaternary (Hancox et al 1986). The Moonlight Fault Zone to the west consists of a series of north to north-northeast striking faults and associated folds. Kinematic analysis of structural data from the Mt Aurum area shows the Moonlight Fault to be a high angle reverse structure dipping towards the west (Barry 1966). The youngest known movement on the fault zone occurred around 8000 years ago (Turnbull and Forsyth 1988). The Nevis-Cardrona Fault System also trends to the northeast and contains several major active faults, a number of potentially active faults and many subsidiary faults (Hancox et al 1985). The youngest known movement within the zone was at least 2000 years ago in the Cardrona Valley (Hancox at al 1986) The Shotover Fault to the north and northwest of the Basin is considered to be potentially active. The ramifications from the presence of active faults in the area are discussed in Chapter Four.

2.3 Quaternary Geology and Geomorphology

2.3.1 Background

Evidence from deep sea drill core obtained 250km east of the South Island indicates that the southern half of New Zealand has been subjected to nine periods of glaciation in the last 700,000 years (Suggate 1990). Uplift and erosion has, however, left a gap in the glacial record between 2.1 - 0.35 Ma in the South Island (Suggate 1990).

The stratigraphic (and chronological) relationships between glacial outwash and interglacial shoreline deposits in the north Westland-Nelson region have been well preserved, and four glacial periods have been identified (Table 1). This glacial sequence is generally taken as the standard for correlation of mid-late Cenozoic South Island glaciations (Suggate 1990). Separate, but similarly local glacial chronologies have been determined in other South Island regions that have been subjected to glaciations, and where the glacial deposits are sufficiently well preserved (eg Canterbury - Soons 1963, Soons and Burrows 1978; Central Otago - McKellar 1960, Brooks 1986).

Bell (1992) suggests a glacial chronology for the Wakatipu Basin and surrounding area by which he correlates the local glacial deposits with the South Island chronology (Table 2). This has been based in part on lithological composition of (glacial) sedimentary deposits, topographic and stratigraphic positions of glacial deposits, radiocarbon dates, and the degree of weathering of deposits.

2.3.2 Waitiri Advance

Exposed in Tobins Track, on the northwestern edge of the Crown Terrace, is nearly 30m of gravelly sand overlying schist at an approximate elevation of 580m asl. This deposit may be described as:

Light orangey brown; SW; dry to moist; highly compact; poorly sorted; massive; fine gravelly fine SAND, with minor cobbles. Clasts predominantly angular to subangular greyschist with some rounded greywacke. Upper 2-3 metres modified by slope processes.

Access to potential exposures in this area was restricted by the landowner, but it is expected that this gravelly sand is present overlying much of the bedrock bench that butts against the Crown Range, underlying younger alluvial fan gravels. Preservation in

OXYGEN ISOTOPE STAGE	AGE KY Imbrie et al 1984	GLACIATION	INTERGLACIAL	GLACIAL ADVANCE Suggate 1965	GLACIAL FORMATION Suggate	SHORELINE FORMATION 1985
1	0		Aranui			Nine Mile
				Kumara 3	Moana	
				Minor	*interval*	
2	12	Otira		Kumara 2/2	Larrikins	
				Important	*interval*	
4	59			Kumara 2/1	Loopline	
5	71					Awatuna
			Kaihinu			
						Rutherglen
6	128	Waimea		Kumara 1	Waimea	
						Karoro
7	186		Karoro			
						Scandinavia
8	245	Waimaunga		Hohonu	Tansey	
9	303					
10	339	Nemona			Cockeye	

Table 1: Sequence of glacial and interglacial units, north Westland (from Suggate 1990, with oxygen isotope ages from Imbrie et al 1984).

PERIOD	EVENT	DESCRIPTION
Waimaungan Glacial	"pre-Waitiri Advance"	till remnants 10m+ thick in Brackens Gully and Eight Mile Creek at 850m asl; ancestral Shotover River flowing north of Coronet Peak deposits 150m of fluvial sediments in Deep Creek; ice limits Roaring Meg and Athol;
Waimean Glacial	Waitiri Advance	Arrow River draining towards the southwest before the onset of ice; ice limit during advance Waitiri Spur - 50m thick deposit till at 340m asl; excavated valley floor 600m asl - Crown Terrace, till veneer; ice lobe up Arrow Valley, drainage to the north - ponded fluvial sediments near Macetown; during ice retreat Arrow River possibly flowed along base of Crown Range.
Oturian Interglacial		freshwater limestones deposited near Eastburn on the Crown Terrace (possible early Otiran interstadial); possible age 32,000yr
Otiran Glacial	Gibbston Advance	Arrow River draining towards Lake Wakatipu via Lake Hayes before onset of ice; cooling began 27-28,000ya; ice terminus Gibbston Basin and Kingston 26,000ya (Otiran maximum) dated from lake sediment over till at Cowcliff Hill; ice confined to Wakatipu Basin
	unnamed late Otiran	glacial oscillation 25-15,000ya, Arrow River in present course deflected by glacial lobes, Shotover possibly flowed east along the base of Coronet Peak to join the Arrow River; ice lobes into Lake Hayes and Arthurs Point
Aranuian Interglacial		ice retreat from 15,000ya; Shotover River building delta into Lake Wakatipu-Lake Hayes; formation of high level lake beaches; lake level lowered by downcutting outlet at Kingston; Kingston outlet abandoned around 5000ya, establishment of Kawarau outlet

Table 2: Sequence of glacial events in the Wakatipu region (from Bell 1992).

the southern part of the terrace is poor. Erosion and infilling by streams originating in the Crown Range has obscured the record in this section. Bell (1992) identified a 50m deep channel cut into bedrock at the foot of the Crown Range infilled with younger lacustrine sediments, and suggests that an ancestral Arrow River may have been active along here, possibly deflected by ice remnants.

On the basis of the massive, poorly sorted, compact nature of the deposit and the abundance of rounded greywacke clasts, it has been interpreted as a basal till. Bell (1992) correlates this deposit with till and ice marginal deposits preserved on the Waitiri Spur east of Victoria Basin, and suggests that the Waitiri Spur was the eastern-most limit of ice during this advance (hence "Waitiri Advance"). The bedrock bench (at an elevation 580 - 600m asl) that underlies the Crown Terrace is inferred to be the remnant of the valley floor that either pre-dates, or is contemporaneous with, the Waitiri Glacial Advance. Bell and Swanson (1977) assigned these deposits to the Waimean Glaciation on the basis of weathering rinds on greywacke clasts, the degree of weathering of deposits, and the degree of fluvial downcutting. However, on the basis of revisions made to glacial chronologies in the Cromwell Basin, D.H. Bell (pers comm) suggests that they may be considerably older.

2.3.3 Post-Waitiri Lacustrine Deposits

Lacustrine sediments, including freshwater limestones, have been identified by Bell (1992) infilling the bedrock channel cut into bedrock (mentioned above) near Eastburn on the southern end of the Crown terrace (Figure 11). Swanson (1977) identified several pond or lake dwelling species of the mollusca phylum, a diverse collection of ostracods species commonly associated with swampy lake margins, and several insects within the limestone. He notes that the assemblages are similar to those in littoral zones of present-day South Island alpine lakes. Faunal similarities with Lake Hayes material has also been noted (Bell 1977a). Plant remains suggest increased sedimentation and

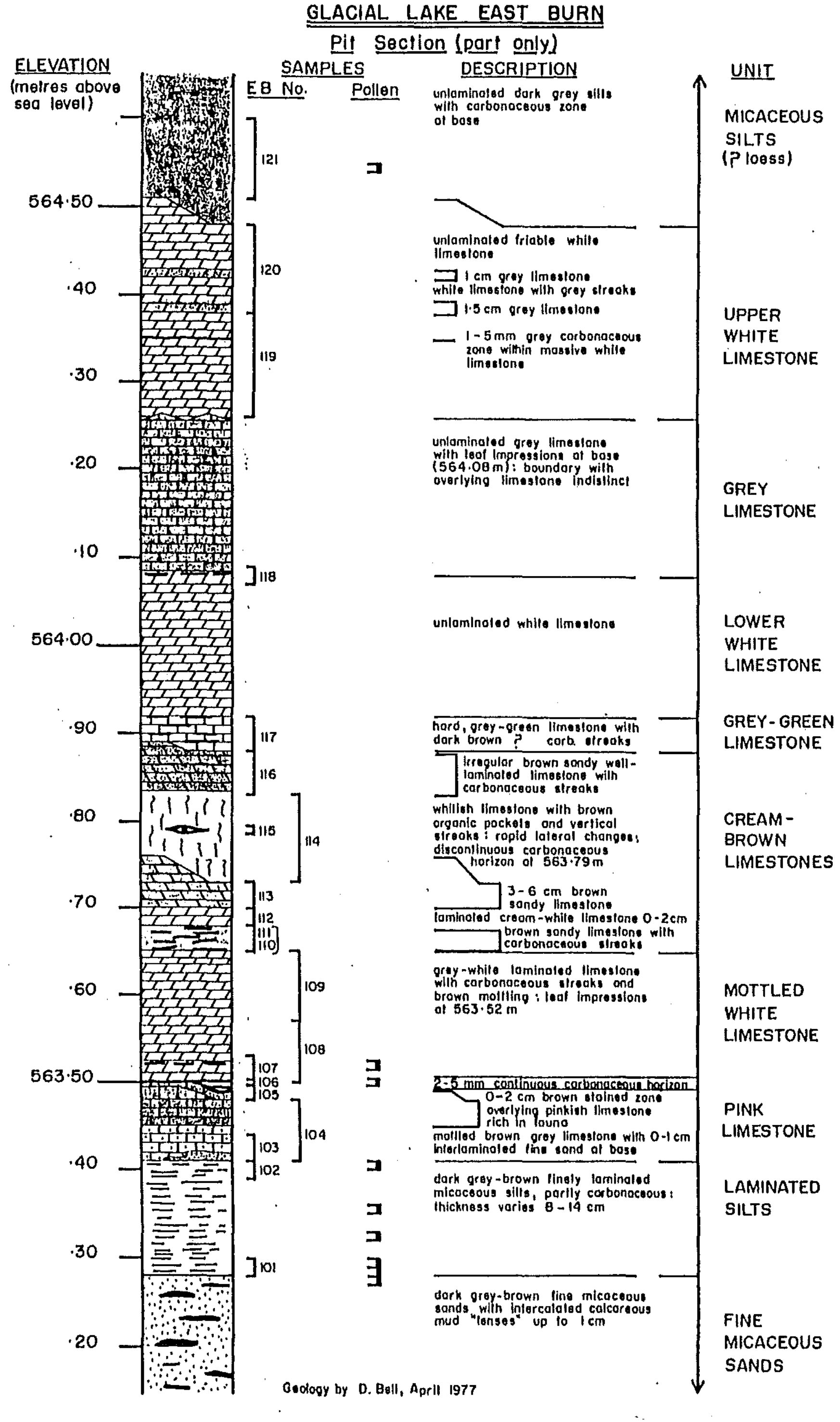

Figure 11: Eastburn lacustrine section (from Bell unpubl.)

shallowing of the lake (Swanson 1977), and Bell (1977b) infers that the deposit represents an upward warming sequence, accompanying a shrinking and drying out of the lake.

A study of the pollen assemblage has identified a mixed podocarp-fern assemblage (Bell and Swanson 1977). Although there is a lack of definitive palynological data from reliable stratigraphic positions within this part of the New Zealand chronology, Bell and Swanson (1977) have interpreted this assemblage, combined with freshwater fauna above, as representing either a full interglacial period or possibly an interstadial period. The lacustrine sediments lie stratigraphically above the Waitiri Advance till and so are inferred to have been deposited during the Oturian interglacial, or possibly during an early-mid Otiran interstadial.

A small gully towards the southern end of the terrace exposes a 15m thick succession of interlayered gravelly sands, sands and silts overlying slightly kinked pelitic greyschist at an elevation of approximately 560m asl (Figure 12). A gravelly sand with sand layers is overlain by one to two metres of compact, massive fine sandy silt, which in turn grades up into a 4m of loose to compact, poorly sorted, massive fine sandy fine to medium gravel with occasional cobbles and a trace of micaceous silt. This gravel is slightly imbricated and gently to moderately inclined to the northwest, and is predominantly subangular to subround greyschist with abundant greenschist and occasional greywacke. It fines upwards into a thinly layered fine gravel, inclined to the northwest, with layers of silt which become thicker and more frequent upwards until the outcrop is dominated by thick anastomosing beds of silt with medium sandy fine gravel between.

These sediments are inferred to represent interglacial fluvial-deltaic-lacustrine sediments deposited in bedrock depressions cut by post-Waitiri fluvial activity (contemporaneous with the Eastburn lacustrine sediment).

Figure 12: Post-Waitiri deltaic - lacustrine sedimentary sequence, Crown Terrace. Steeply dipping, pelitic greyschist is overlain by a succession of interbedded gravelly sand, silt, and bedded sandy fine to medium gravel (centre left), which fines progressively upwards into anastomosing layers of bedded silts (upper right).

2.3.4 Gibbston Advance

Bell (1977, 1992) describes exposures near Cowcliff trig that consist of approximately 10m of till overlain by 6-8m of horizontally bedded micaceous silts and carbonaceous mud (Figure 13). Two species of ostracod found within the lacustrine silts suggest that they were deposited in a shallow, high energy environment such as a small channel pond or a proglacial lake extending west from Cowcliff (Bell and Swanson 1977).

Bell (1992) has correlated the Cowcliff till to a moraine-like deposit in the Gibbston Basin and to the moraines at Kingston, citing glacier profiles constucted by Mathews (1965) to support this conclusion. This Gibbston "moraine" has, however, been interpreted by others as a landslide deposit (R Thomson pers comm, IGNS in prep). The lacustrine silts at Cowcliff have been radiocarbon dated at 25,500 ± 800 ya (Bell and Swanson 1977), implying a late Otiran age for the underlying Gibbston Advance till - possibly around 27,000ya (Bell 1977a).

The ice would have been confined to the Wakatipu Basin by the edge of the Crown Terrace and the surrounding ranges during the Gibbston Advance, but it is unknown to what depth the basin floor was exhumed at this time.

2.3.5 Sugar Loaf and Queenstown Hill Till

Preserved on the southern flanks of Sugar Loaf, between about 850 and 900m asl, is a series of low linear ridges running approximately parallel to the slope. To the west, towards Queenstown Hill, these are replaced by a series of arcuate transverse ridges (open towards the west) which lead down into a shallow topographic depression or hanging valley behind Queenstown Hill (Figure 14). Exposed in a small stream in this valley at approximately 750m asl are at least 4m of light grey, compact, massive, sandy

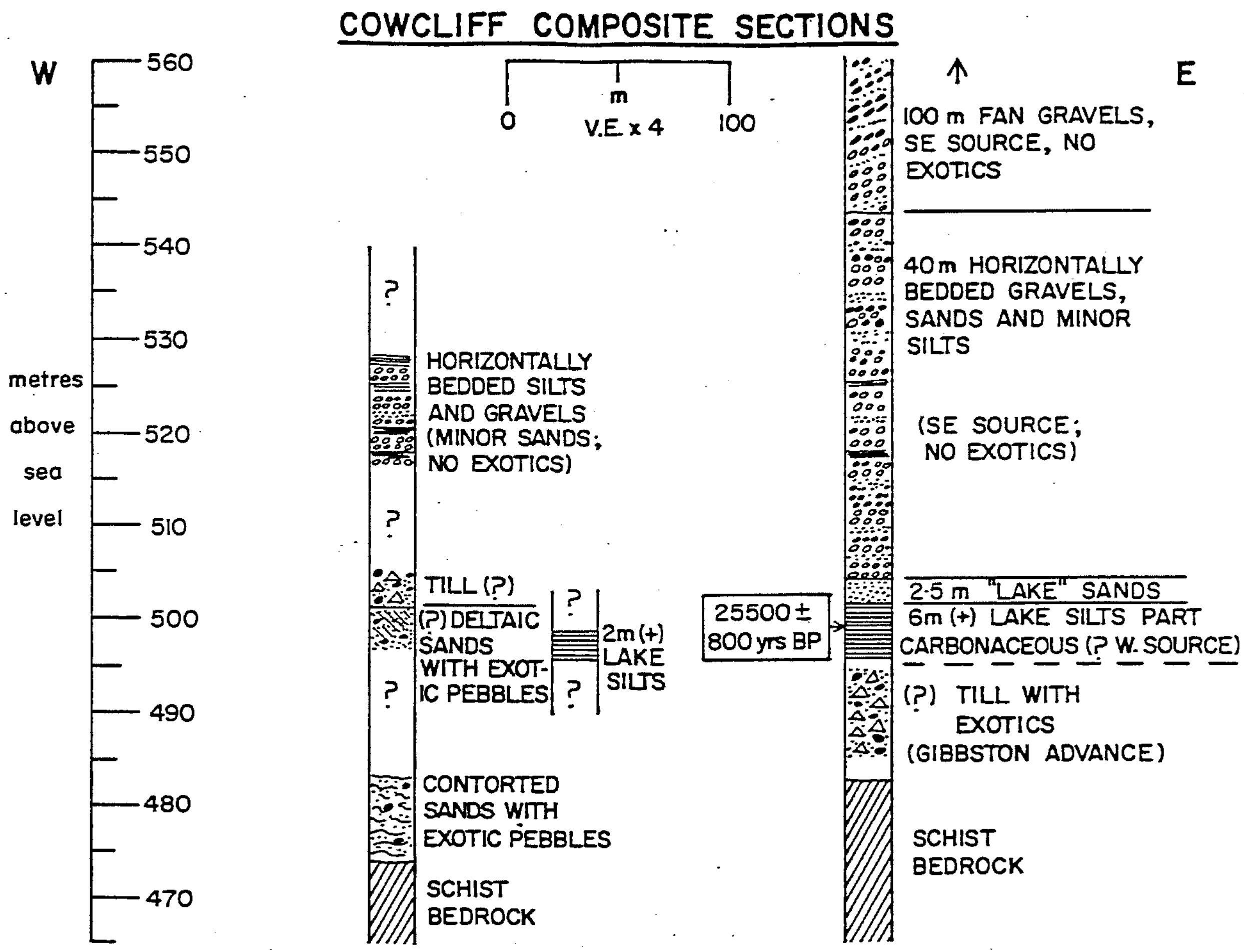

Figure 13: Cowcliff composite section (from Bell unpubl.)

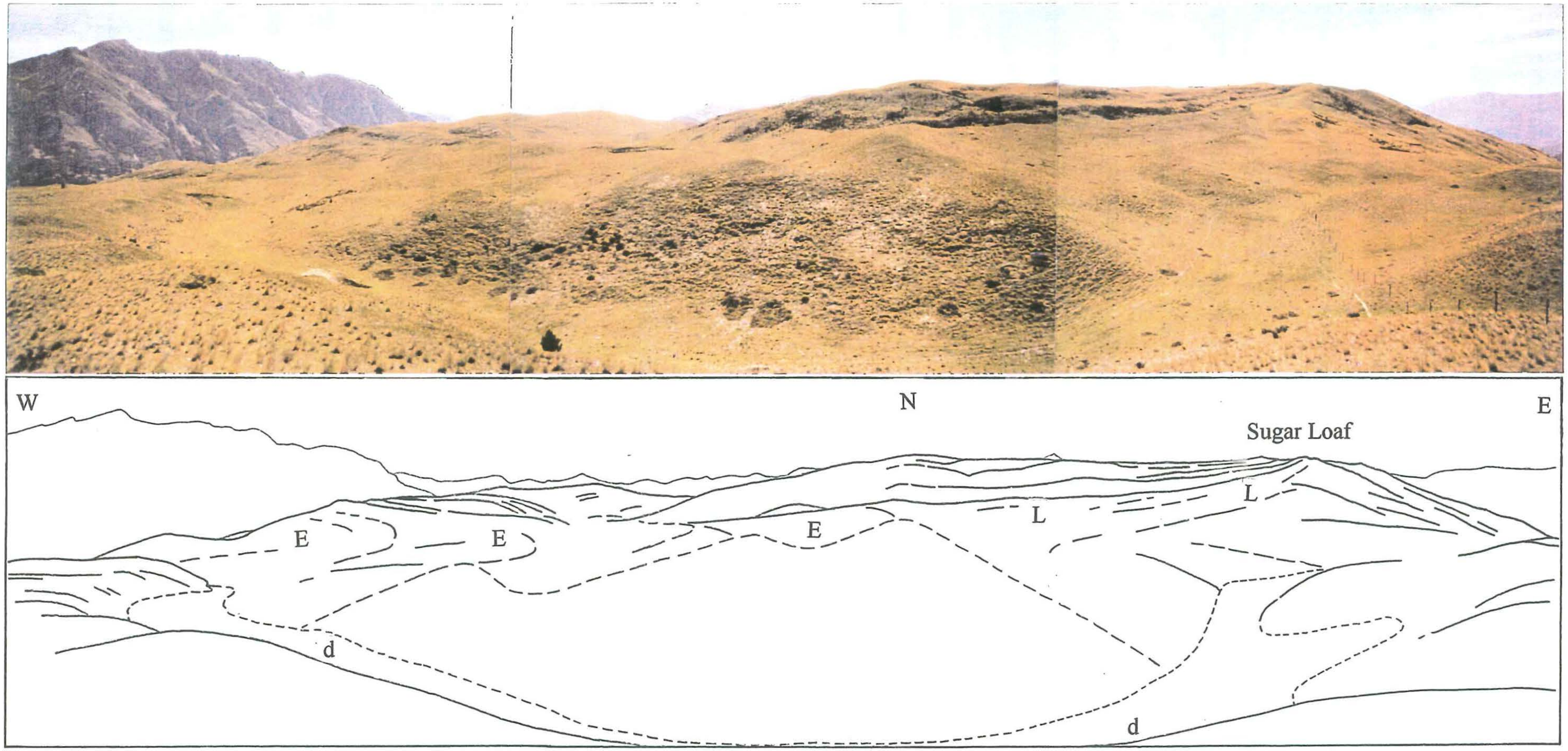

Figure 14: The Sugar Loaf linear lateral moraines (L), and the Queenstown Hill arcuate end moraines (E). Relict drainage channel in foreground.

fine to medium gravel with some cobbles, overlying bedrock. The gravel is predominantly schist but contains abundant rounded greywacke clasts. Similar gravels are poorly exposed in old alluvial gold-mining workings upslope to the east. It is assumed that these gravels occupy much of the valley, and that a considerable thickness of gravel overlies bedrock on the southern flanks of Sugar Loaf.

The gravel is interpreted as being a till deposit on the basis of its massive, compact nature, and the abundance of greywacke clasts. The linear and arcuate ridges are interpreted as being lateral and end moraines deposited as ice retreated towards the west. There is insufficient evidence to determine whether the Sugar Loaf moraines and Queenstown Hill moraines are part of the same retreat phase, or if they result from separate advance and retreat cycles. It is most probable that the Queenstown Hill moraines represents a younger, less extensive ice advance.

The elevation of the tills, between ~720-900m asl, suggest that they may be comparable in age to the Waitiri (Waimean Glaciation) or Gibbston (late Otiran Glaciation) glacial advances. Wood (1962) included them in his "Camp Hill Formation" which he classified as being generally contemporaneous with the Hawea Glacial Advance (Otiran Glaciation).

2.3.6 Youngest Glacigenic Deposits (undifferentiated)

Preserved at relatively low elevations along the ice sculpted ridges in the Basin, and on the lower slopes of hills are remnants of glacigenic material deposited during the general waning of the late Otiran glacial period. The stratigraphic situation is complex. A series of minor ice advances coupled with poor preservation and lack of exposure have meant that determination of a glacial deposit chronology is beyond the scope of this study. Because exposure was generally poor, and confined to road cuts and river banks, the distribution of materials has been based largely on geomorphology. All post-Gibbston late Otiran glacigenic deposits have been mapped as one unit which incorporates a variety of materials including basal and ablation till, moraine, ice marginal deposits, and outwash gravels. The following are examples of exposures:

(A) ***Kame Terrace Alluvium***

Lewandowski (1976) and Watts (1988) describe kame terrace deposits preserved on the lower western slopes of the Remarkables. They can be generally described as

> *Light greenish grey to dark greyish brown; UW-SW; moist; loose to compact; poorly to well sorted; massive to faintly bedded; sandy fine to coarse GRAVEL, with some silt and rare cobbles. Occasional silt and sand lenses. Occasional large rounded erratics (1.5m diam.). Clasts predominantly rounded to subangular schist, quartz and greywacke. Fines non-plastic. Moderately permeable.*

Kame terraces are a stratified accumulation of gravels deposited by streams flowing between the glacier and the side of a valley, possibly into standing water (Sugden and John 1977). The gravels are chiefly derived from debris within/on the glacier, with secondary/subordinate input from landbased streams and colluvium (Flint 1971). Kame terraces are usually modified (deformed) during and after deglaciation. Wood (1962) described these gravels as part of the Camp Hill Formation (contemporaneous with Hawean).

(B) ***Littles Road Ice Advance and Retreat***

At the foot of Coronet Peak is a narrow valley excavated into bedrock, that opens out to the Shotover River to the southwest, and which is enclosed to the northeast by a steep cliff 40 to 50 metres high. Schist is exposed in the southeast slope, landslide debris forms much of northwest slope.

Exposed in Malaghans Road above the end of the valley:

Light greyish brown to medium orangey brown; SW; moist; loose to compact; poorly sorted; massive; fine to coarse sandy fine GRAVEL, with minor silt, occasional cobbles and SW angular schist boulders. Clasts predominantly subangular schist and quartz, occasional subrounded greywacke. Occasional coarse sand lense.

The ground surface has several circular/concave depressions up to ~2m deep. inferred to be kettle holes. The gravel is interpreted as a moraine deposited by the ice that cut the bedrock valley. Outwash terrace remnants built out towards the northeast are:

Medium brownish grey to orangey brown; SW; dry to moist; loose to compact; poorly to well sorted; massive to slightly bedded; medium to coarse SAND, sandy ine GRAVEL, fine GRAVEL, gravelly fine SAND, with occasional cobbles. Clasts predominantly subangular to subrounded tabular schist and quartz, with occasional to minor rounded greywacke.

In the ice cut valley, on the upper slopes in a road cut on Littles Road is;

Dark orangey brown; SW; moist; loose to compact; poorly sorted; slightly bedded, gently undulating; flat lying clasts; medium to coarse sandy fine GRAVEL, with occasional cobbles. Clasts predominantly angular to subrounded schist with minor greywacke. Occasional thin layer sand, and coarser chaotic lense.

The road cut shows a progressively fining sequence downslope towards the centre of the valley to;

Dark greyish brown; UW-SW; moist; firm; micaceous silty fine SAND with very thin horizontal layers of sandy fine GRAVEL and occasional cobbles.

These sedimentary areas are interpreted as having been deposited in a low energy environment, possibly a proglacial lake trapped in the gully as ice retreated.

(C) *Dalefield Till and Fluvioglacial Gravel*

Exposed in a deeply incised gully opposite Tuckers Beach and in the Shotover River bank (Figure 15) overlying schist are 20 to 40 metres of

> *Light to medium brownish grey, UW-SW; moist; loose to compact; moderately well sorted; coarsely to finely layered, gently inclined; fine to medium SAND and sandy GRAVEL. Clasts predominantly subangular to subrounded schist, minor greywacke. Large cross bed sets and trough cross bedding.*

These are interpreted as fluvial (possibly deltaic) gravels, possibly proglacial, and are overlain by 20 to 30 metres (Figure 16) of

> *Light brownish grey; SW; moist; compact; poorly sorted; massive; chaotic; fine sandy GRAVEL, with minor cobbles and occasional angular schist boulder (1m diam.). Clasts predominantly subangular to subrounded schist with abundant greywacke.*

The two deposits are separated by an irregular, erosional contact. The compact gravel is interpreted as a till deposited during a readvance of ice from the west/northwest. Overlying the till, separated from it by a sharp erosional contact, are two to ten metres of interbedded and crossbedded fine and medium sands, subhorizontal to gently incline to the northwest.

Figure 15: 20 to 40m of interbedded sand and sandy gravel of the Dalefield fluvioglacial deposit, overlain by the Dalefield till (upper left). The irregular, erosional contact is marked by the tree line.

Figure 16: Cross-bedded sands in sharp contact with the underlying compact, sandy gravel (Dalefield Till) exposed in a deeply incised gully below Dalefield. View is to the southeast, with the Shotover River in the distance.

A general description of till veneer preserved elsewhere in the Basin;

Medium brownish grey to orangey brown; SW; moist; compact; poorly sorted; sandy fine GRAVEL, fine gravelly SAND, silty fine SAND; silty fine GRAVEL, with cobbles. Clasts predominantly subangular to subrounded schist and quartz, minor greywacke. May contain occasional lenses of sorted silt/sand/gravel.

2.3.7 Greater Lake Wakatipu Lacustrine Sediments

Exposed in a small quarry near the outlet of Lake Hayes, and in Hayes Creek itself, is at least 6m of finely laminated, very fine to fine sandy silt, occasionally containing thin lenses of gravelly fine sands. Similar laminated silts outcrop in a dry gully about 300m north, in a farm-track cutting at the base of Slope Hill, and in the S.H.6 road cut west of Hayes Creek (Figure 17). In the gully, the laminated silt in the gully grades laterally and upwards into massive silts, fine sands, and fine gravelly sands. These in turn give way to loose, layered sandy fine schistose gravels that coarsen towards the southwest.

South of the Kawarau River, opposite the turnoff to Kelvin Heights, more than 8m of finely laminated, micaceous silt and very fine sand is exposed in a road cut along SH6 (Figure 18). Similar silt is exposed in the north and south banks of the Kawarau River as far as the Kawarau Falls Station, and in road cuts along SH6 as far south as the Remarkables Skifield access road turnoff.

Small, isolated outcrops of predominantly massive silts and fine sands occur along the northern shores of Frankton Arm, on the Kelvin Height Peninsula, and along the southern bank of the Kawarau River below the Remarkables.

These silt deposits appear to attain a maximum elevation of approximately 330m asl in the Kawarau Falls vicinity, and it is inferred that they exist to some depth below the flat

Figure 17: Finely bedded lacustrine silt exposed along S.H.6 south of Lake Hayes (vie towards the south). The deformation is inferred to be the result of consolidation and differential settlement within the silt unit as it became stranded by the progressive lowering of Lake Wakatipu.

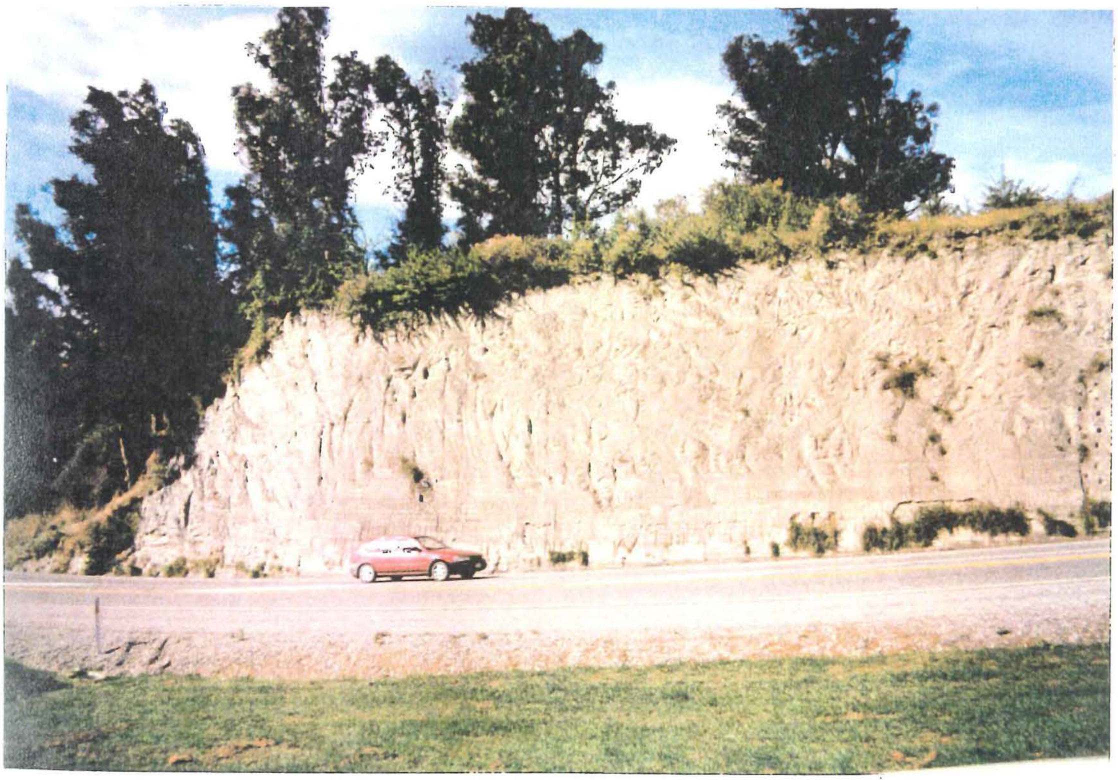

Figure 18: 12 to 15m of firm, finely laminated (varved), micaceous silt and very fine sand lacustrine deposit exposed in S.H.6 south of the Kawarau River. The upper terrace is at an approximate elevation of 320 to 330m asl, and represents the maximum aggradation level of the Greater Lake Wakatipu lacustrine unit.

area between Peninsula Hill and the Remarkables (two boreholes at the western foot of the Remarkables, near SH6, record silts and silty gravels to a depth of at least 37.5m., underlying recent alluvial fan gravels - refer to Figure 4 in map pocket), and on the north side of the Kawarau River. South of Lake Hayes it is assumed that the silts have limited surficial extent, as they grade laterally into gravels towards the west, but are expected to occur at depth.

These silts and sands are interpreted as lacustrine sediments deposited during a period when Lake Wakatipu was much enlarged during the final retreat of glacial ice and occupied the narrow bedrock depression between Lake Hayes and Frankton Arm, and probably extended north towards Dalefield. Further evidence of previous high lake levels are the numerous high level beach terraces perched up to approximately 50m above the present level of Lake Wakatipu. It is assumed that these lacustrine sediments are present to some depth below the Ladies Mile and Frankton Flats, and possibly also anywhere towards Dalefield or north of Lake Hayes.

2.3.8 The Shotover Delta and other Fan-delta complexes

Exposed in the western bank of the Lower Shotover River, between the SH6 bridge and the confluence of the Shotover and Kawarau Rivers, is 25-30m of sandy gravels and gravelly sands with minor silt lenses. General description;

Medium greyish brown; UW; moist; loose to compact; poorly to moderately well sorted; coarsely to finely bedded, gently to moderately inclined to the south, and cross-bedded; fine gravelly coarse SAND to sandy fine to medium GRAVEL, with minor silt lenses, occasional cobbles. Clasts predominantly subangular schist and quartz, minor rounded greywacke.

The deposit includes lenses and layers up to one metre thick of firm, finely laminated silts and sands, compact sands, and soft crossbedded quartzose sands. It is interpreted that these gravels were deposited as a delta by the Shotover river when Lake Wakatipu extended into Lake Hayes. As mentioned previously, the sand and gravel content of the lacustrine silts south of Lake Hayes increases towards the southwest (Figure 19). The contact formed as the delta built out into the lake is inferred to be gradational between the lacustrine deposits and overlying deltaic gravels is inferred.

The low, slightly inclined surface that comprises Frankton Flat, Ladies Mile Flat, and the Domain Road-Lower Shotover Flat is inferred to be the aggradation surface of the delta plain (the subaerial part of the fan-delta complex which is dominated by fluvial processes). The elevation of this surface is 360 to 350 m asl gently inclined towards the south. Poor exposures along the eastern bank of the Shotover River to the north of the Shotover bridge, display firm to loose, interlayered gravelly fine sand and fine to coarse gravel, with occasional cobbles, and some cross-bedding and trough cross-bedding.

Locally exposed in a small gully are six to eight metres of interlayered silts, hard, dry and very fine sands, and sandy fine gravels, featuring load structures (injections of silt into overlying gravel layer), and convoluted folds of fine grain sediments (Figure 20). This deposit is interpreted as a small lake beside or within the delta, or possibly as a proglacial lake deposit with periodic influx of gravelly debris.

Several other, much smaller, fan-delta complexes are present at different levels in the Basin. The most prominent of these are the Two-mile Creek, One-mile Creek and Marina Heights deltas that have built out to an elevation of 344-45m asl. These have been noticeably truncated as the lake level dropped rapidly. They may be generally described as;

Medium greyish brown; SW; loose to compact; poorly to well sorted; finely to coarsely bedded, layers gently to moderately inclined; fine to coarse sandy fine to

Figure 19: Deltaic, sandy fine to medium gravel exposed in a river-cut bank below the Ladies Mile Flat aggradation surface. Contains several lenses of silt and sand.

Figure 20: Six to eight metres of sub-horizontal interlayered silts, very fine sands, and sandy fine gravels. This succession is interpreted as representing periodic (possibly seasonal) influx of coarser material into a low energy (lacustrine) environment. Note the deformation of the fine grained layers (load structures).

medium GRAVEL with minor pebbles. Clasts predominantly angular to subangular schist, with minor subrounded to rounded greywacke.

Watts (1988) describes fan-delta complexes from the western slopes of the Remarkables at an elevation of approximately 360m that have built out from the kame terrace material as;

Light grey; UW; loose to compact; well to poorly graded; finely to coarsely bedded, sub-horizontally to gently inclined; sandy fine to medium GRAVEL, with occasional lenses of gravelly sand and gravel. Clasts subangular to subrounded schist, quartz and greywacke.

2.3.9 Beach Deposits

On the east-facing slopes above Lake Hayes is a series of small benches at three distinct levels (Figure 21). The elevation of each was estimated from the 1:25,000 topogaphic map to be 330m, 365m, and 400m asl. Poorly exposed in these benches are between one and two metres of:

Light to medium orangey brown to brownish orange; loose; finely to coarsely bedded, layers sub-horizontal to gently inclined; imbricated; medium to coarse sandy fine to medium GRAVEL and gravelly SAND, with occasional lenses fine sand. Clasts predominantly tabular, subrounded schist. Moderately to highly permeable; Fe stained.

Similar benches have been preserved on the slopes on the opposite side of the lake. One prominent small bench occurs at approximately 400m asl on the slopes to the north of Speargrass Flat Rd (between Hunters Rd and Lake Hayes) (Figure 22). Low, arcuate, splayed ridges northeast of Lake Hayes at an elevation of approximately 350m asl,

Figure 21: Relict beach terraces preserved above Lake Hayes that represent higher lake levels of approximately 400m, 365m and 330m asl (Greater Lake Wakatipu). View is towards the southwest.

Figure 22: High level lake bench above Speargrass Flat Road at approximately 400m asl. Small truncated fan-deltas in valley probably built out at a lake level of approximately 380m asl. View to the north.

consisting of gravel similar to that described above, are interpreted as storm-wave deposited berms. A series of wave cut benches is preserved at Frankton, incised into the deltaic gravels, leading down to the present lake beach. These high level benches are interpreted as being remnants of successive high level beaches cut by the progressively shrinking "Greater" Lake Wakatipu.

Beach deposits are also preserved above Peninsula Rd, overlying bedrock, at an elevation of around 340-350m asl. At least 2m of beach gravels, similar to those at Frankton, outcrop on the low lying part of the peninsula between the golf course and Peninsula Hill. There is a significant beach terrace at an elevation of approximately 340m asl in Queenstown, corresponding to the Queenstown camping ground and the Melbourne St surfaces. Beach gravels can be found exposed on this surface, and in isolated patches on the slopes below.

In summary, four prominent high level lake beaches have been identified (elevations estimated off topo maps). These being at approximately, 400m, which corresponds to the level of the 'perched' Lake Johnson, 365m, 345m and 330m asl. Several less extensive surfaces also occur. Bell (1992) identified high level beaches at 354m, 337m, and 315m asl which he dated at ~9500ya, 8930±91ya (14C date from wood sample in lake silts below bench), and ~5000ya respectively.

2.3.10 Alluvial Fan Deposits

A number of large coalescing alluvial fans have built out over the Crown Terrace from the Crown Range (Figure 23). May be generally described as:

Light brownish grey; UW; loose to compact; poorly to well sorted; massive; fine to coarse GRAVEL, with some sand, and rare cobbles and silt. Clasts subrounded to subangular schist. Non-plastic. Occasional silty fine sand lenses. (Watts 1988).

Figure 23: Otiran-age alluvial fan gravels overlying bedrock, Crown Terrace. Note the deeply incised gully. View is to the southeast.

These alluvial gravels overlie the Waitiri Advance till and the Eastburn lacustrine sediments, and therefore are interpreted as being post-Waimean in age. They were probably at their most active during the Otiran glacial stage. The streams have since become deeply incised into the bedrock of the terrace.

Several high level alluvial fans have also been preserved overlying kame terrace deposits on the east-facing slopes of the Remarkables. Due to their stratigraphic relationship to the kame deposits, it is inferred that these fans also date from some time during the Otiran.

There are many recent "post-glacial" alluvial fans in the Wakatipu Basin, from intermittent and permanent streams draining the ranges and low-lying hills. Feeder streams have become deeply incised into some, while others are periodically aggrading especially during high intensity rainfall events. The texture and structure is variable due to the nature of the deposits., but may be generally described as;

Light to dark brownish grey; loose to compact; poorly to well sorted; fine to coarsely bedded, layers subhorizontal to gently inclined; sandy fine to medium GRAVELS, with minor layers of silty sand. Clasts predominantly subangular to subround schist and quartz, minor greywacke. Occasional cross-bedded layers of fine to medium sand.

2.4 Geomorphic Evolution

2.4.1 Structural Controls

Tectonic activity has been an important factor in the geomorphic development of the Wakatipu Basin. Differential uplift caused by compressional deformation during the Kaikoura Orogeny between the early Miocene and the early Pleistocene had a major effect on the development of the late Tertiary drainage pattern. Northeast-southwest trending faults were soon exploited by rivers which became progressively entrenched with continued uplift in the early to mid Pleistocene. The Nevis and Cardrona rivers were established by the late Tertiary, and it is inferred that the Oreti-Von-Dart, and the Arrow-Shotover-Mataura river alignments (corresponding to the west and east arms of the present day Lake Wakatipu) were developed during the same period (Bell 1992). Uplift during the Kaikoura Orogeny to the west was also partly responsible for the onset of glacial activity by providing the topographic relief required for glaciation.

Bedrock strength and foliation attitude have also been a major control on geomorphic evolution in the region. Foliation provides a weakness that can be exploited by waterways and as such it has been important control on development of drainage patterns (and hence valley systems), and on the development of assymetrical valleys (Bell 1992). Joints are also a factor in the evaluation of the landscape, as they are a control on slope modification, particularly in steep slopes, through rock falls and topples etc.

Continuing uplift to the present day has resulted in further incision of rivers into the bedrock (eg the Kawarau Gorge).

2.4.2 Glacial Modification

When topographic and climatic conditions were conducive to glaciation, ice from the north/northwest presumably exploited the inferred N-S drainage systems, modifying catchments by cutting through drainage divides and deepening valleys.

Successive ice advances have obliterated much or all of the features of previous advances. Only the features formed during the most extensive, and youngest ice advances have been preserved.

Typical, ice-erosional landforms that characterise the Wakatipu landscape include the bedrock troughs that form Lake Wakatipu, Lake Hayes and Lake Johnston (Figure 24), the faceted hills, the ice-rounded roches moutonnees and the low, mamillated ridges within the basin (Figure 25), the truncated spurs of the surrounding ranges, and the very prominent Crown Terrace surface and terrace scarp (Figure 26). Glacial depositional features include kame and outwash terraces, moraines, and perched erratics.

Ice retreat probably began around 14,000 years ago (the beginning of the Aranuian interglacial has been placed at this time by pollen analysis in the north Westland sequence, Suggate 1990).

2.4.3 Slope Movement

Slope movements have extensively altered the Wakatipu Basin since the last glacial period. Several different types of slope movement are have occurred in the Wakatipu Basin. They range from large, slow moving bedrock creep (flow) type deformation and translational bedrock slides, to small colluvial slides and flows, rock falls and topples. Movement within bedrock is primarily controlled by the anisotropic nature of the schist,

Figure 24: Ice-excavated bedrock trough occupied by Lake Johnson. Present lake level is 399m asl, maximum depth is 26.8m.

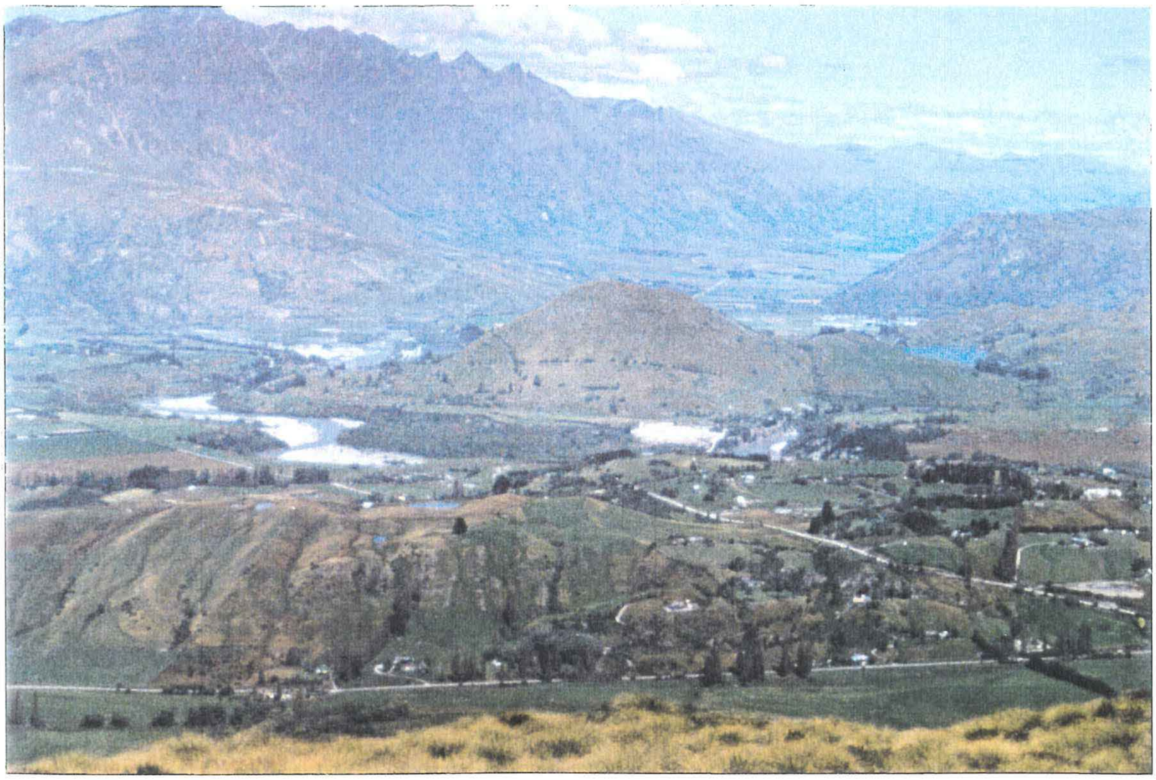

Figure 25: Ice sculpted morphology of the Wakatipu Basin. Low mamillated ridge in foreground, two roche moutonnees (Ferry Hill and Peninsula Hill, centre and to right). "Perched" Lake Johnson to the right. View is to the south.

Figure 26: Slope-movement modified Crown Terrace scarp excavated by ice during the mid to late Otiran Glacial period.

and by defects such as shear and crush zones, and jointing. Failure within engineering soils is controlled primarily by fines content and cohesion, and water content.

Slope movements within and around the Basin were mapped as part of the 1:25,000 engineering geological plan, primarily by analysis of aerial photographs. No specific investigations were carried out for any of the landslides identified. Classification of slope movements follows Hutchinson (1988).

An extensive amount of data on landsliding in schist terrain has been produced as a result of investigations carried out in the Cromwell Gorge as part of the Clyde Power Project. Because of the lack of detailed data on slope movements within the study area, this section draws heavily on data from the Cromwell Gorge case studies and from smaller investigations in the Otago Schist region, to suggest a possible model of slope failure.

Schist is naturally anisotropic - foliation representing planes of weakness. Shear strength parallel to foliation is dependant on mica content and how well foliation is developed. Foliation, foliation shear zones, crush zones (faults) and joints were found to be the major control on the development of landsliding in the Cromwell Gorge (Beetham et al 1991). Foliation shear zones are thin zones of clay-rich crushed schist usually <100mm thick that have developed sub-parallel to foliation during metamorphism and folding, and are common throughout the schist in the region. High to low angle zones of shattered, sheared and/or crushed schist, up to ten's of meters wide, have developed in the region in response to tectonic stresses. Joints developed in response to tectonic stresses and ice loading (followed by unloading), are very closely to widely spaced, often part of (local) joint set, with variable continuity.

Bell (1992) discusses the assymmetrical nature of many valleys in Central Otago and their development in response to the foliation of the schist bedrock. Many failures occur when slope angles are sub-parallel or steeper than foliation. Asymmetry characteristic where foliation dips between 15-30° (Bell and Riddolls 1992). Gillon and Hancox

(1991) note that most of the slides in the Cromwell Gorge have developed either partially or wholly on foliation dip slopes.

Beetham et al (1991) developed a model to explain the development of the Nine Mile Landslide in the Cromwell Gorge. The removal of about 52MPa of static overburden pressure during the downcutting of the Cromwell Gorge has resulted in an increase in the horizontal/vertical stress ratio in the gorge. Coupled with the regional tectonic compressional regime, this results in high horizontal shear stress in excess of the rock strength (Beetham et al 1991). The schist responds by buckling or folding in a downslope direction along foliation (Figure 27). With continued movement, enhanced by gravitational effects and confined groundwater conditions, the multiple defects develop into through-going shear zones that form the basal failure zones for fully fledged landslides (Figure 27). Bell (1992) described similarly oversteepened schist during investigations of the K9 landslide in the Kawarau Gorge.

Present-day landslides in the Cromwell Gorge are primarily translational rock and chaotic debris slides controlled by foliation shears, faults and jointing. Can be broadly described as surface layers of chaotic debris overlying gravitationally displaced schist bedrock over a basal shear zone(s) (note however, that basal shear zones are not necessarily present). Gillon and Hancox (1991) note that the internal structure can be complex, comprising several major shear zones and perched groundwater areas reflecting possible multistage development and stepwise connection along defects (Prebble in press).

The Coronet Peak Landslide - An example of a deep seated bedrock slope failure

Situated on the southern flank of Coronet Peak (forming the northern boundary of the Basin), the Coronet Peak Landslide is a dominant feature of the Basin, covering an area in excess of 23km^2 (Figure 28).

Head scarp(s) of the main body of the slide run along and behind the ridge crest(s) from above Arthurs Point to Coronet Peak itself and down towards Arrowtown. From aerial

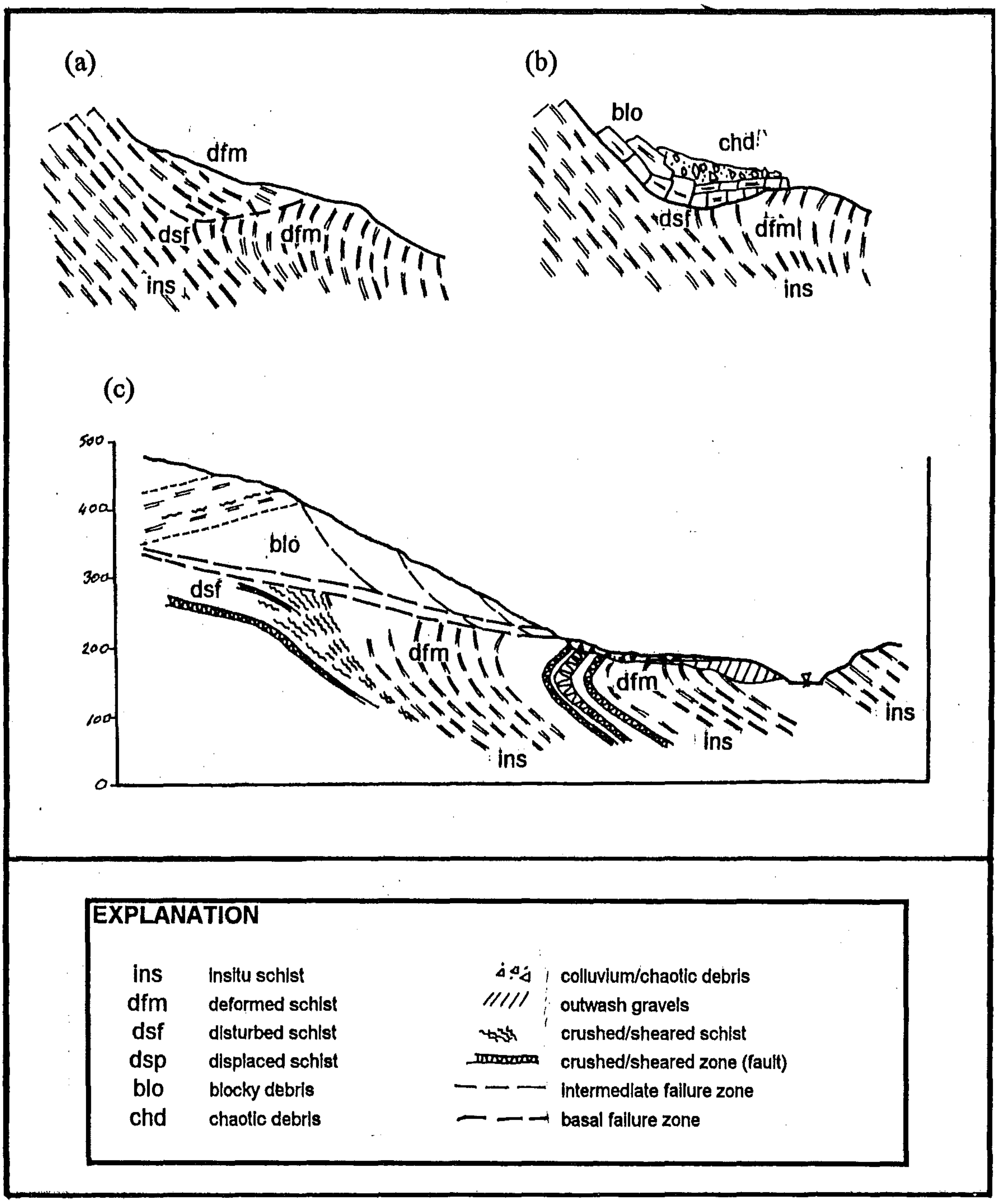

Figure 27: The development of bedrock creep into landsliding with a basal failure zone separating low angle schist landslide from toe buckled schist.
(a) Asymmetric buckling deformation developing along inclined anisotropy of schist under gravity.
(b) Development of basal failure (shear) zone in creeping schist juxtaposing low angle displaced schist over steeply dipping schist.
(c) Example - Nine Mile Creek Landslide, Cromwell Gorge
(from Beetham et al 1991)

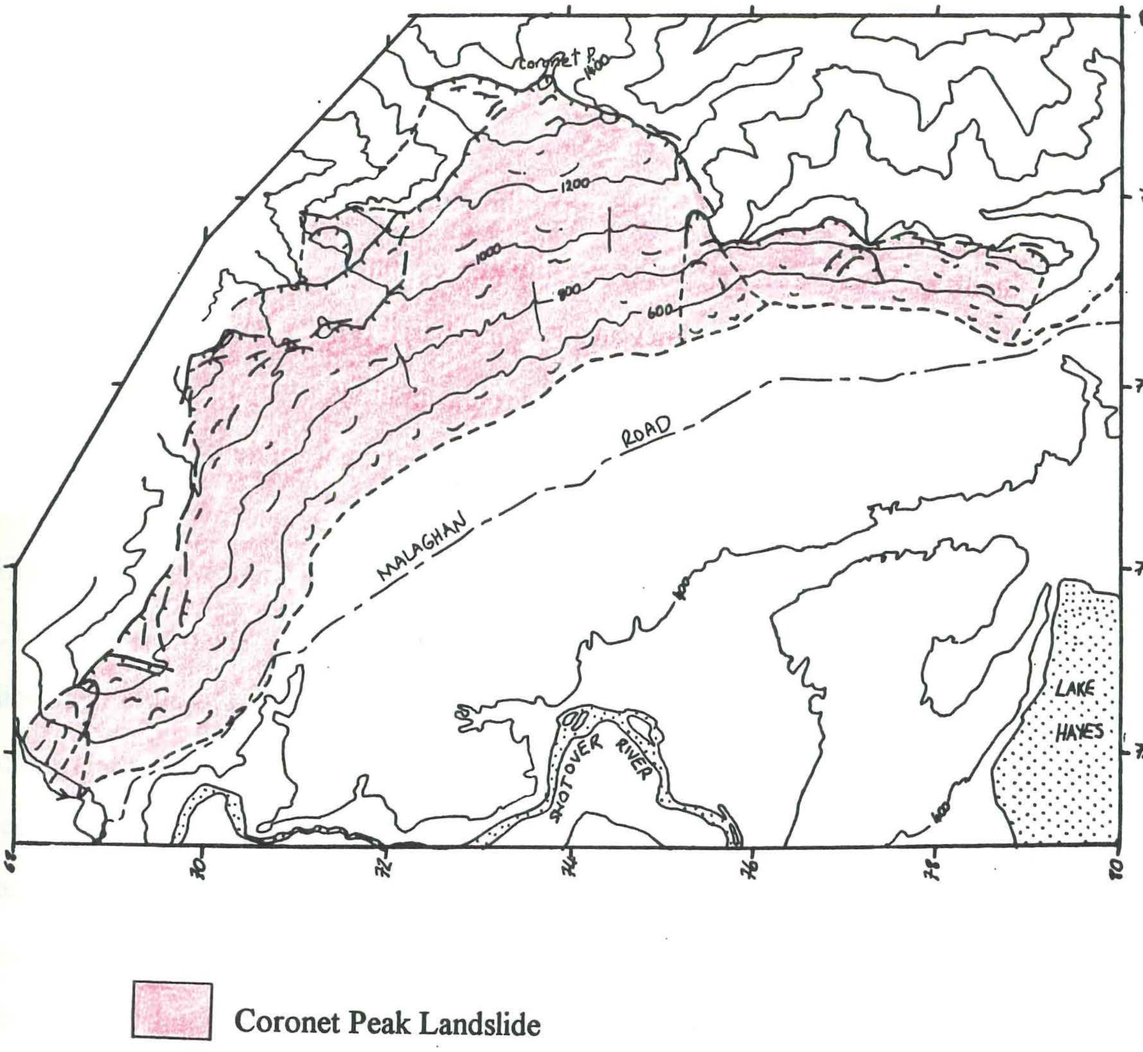

Figure 28: Location of the Coronet Peak Landslide.

photograph analysis the scarps all appear to be in various stages of degradation. It is inferred from aerial photograph analysis that the toe of the slide mass, at least in places, overlies alluvial terraces in the valley floor, although saw no exposures that confirmed this. The surface of the slide mass is very hummocky and irregular, and is subdued. Slide debris exposed in cut road batter is chaotic, predominantly matirix supported (silt and sand) schist debris. Occasional irregular schist blocks are visible within the slide debris, and there are several small ponds and swampy areas on the slide mass. The surface is cut by numerous incised streams that have built small to extensive alluvial fans out into the valley. There are small localised areas of re-activation (Arthurs Pt, and southeast of skifield).

The Coronet Peak landslide is presumed to be controlled by similar mechanisms to the Cromwell Gorge landslides. The average foliation attitude of in situ schist near the slide dips 15° to the south west, which is comparable to the present slope of the landslide, and foliation shear zones and jointing are known to occur in other parts of the area. And has been subjected to similar triggers (unloading of vertical stress by ice erosion of bedrock, then retreat of ice mass and probable fluvial erosion at toe). No oversteepened schist has been observed, but that described in relation to Nine Mile and K9 slides was not discovered until exploratory/drainage drives had been excavated. It is suggested that the creep/translationall slide model be applied to the Coronet Peak landslide.

Present stability - no evidence for large scale movement (possibly very slow creep?), small localised areas of reactivation (Figure 29). Numerous incised streams, well established, not disrupted by debris movement on med-large scale. Future - unlikely to respond to seismic shaking (except small scale debris/rock slide?), as has presumably been sitting there for at least 10,000yrs - has most likely been subjected to large earthquakes in that time. Compare Cromwell Gorge slides no evidence of large scale movement for 16 - 50,000 years, and no evidence of rapid large scale mvt (Gillon and Hancox 1991). No problems associated with skifield development on upper slide mass.

Figure 29: Debris flow reactivation of schist slide debris following heavy rain during February 1994, Skippers Road. View is to the northwest.

2.5 Synthesis

- Nine broad Quaternary surficial units have been mapped overlying Otago Schist in the Wakatipu Basin. No Tertiary-aged sediments are known to have been preserved.

- Structure in the region is dominated by NNE-SSW trending reverse faults. Two significant, active fault systems proximal to the Basin are the Moonlight Fault Zone, and the Nevis-Cardrona Fault System.

- Glacigenic deposits dating from the Waimean and Otiran Glacial Periods have been preserved in the Basin. Several glacial advances and intervening interglacial periods have resulted in a complex stratigraphic and geomorphic situation.

- The glacigenic deposits range from highly compact, massive sandy gravel till, to sorted, bedded fluviglacial sandy gravels and gravelly sands, to bedded lacustrine silts and fine sands.

- During and following final ice retreat (ca. 14,000ya), Lake Wakatipu was at a greater elevation and was more extensive than at present, as evidenced by high level beaches, extensive deposits of lacustrine ilts and fine sands, and high level truncated fan-deltas and alluvial fans. Progressive lowering of the lake water level continued until the lake reached its present level sometime after 5,000ya.

- Extensive slope instability in the schist terrain exposed by ice retreat, controlled primarily by foliation and rock mass defects, and triggered initially by ice erosion and retreat. The Coronet Peak Landslide is probably at least 14,000 years old.

CHAPTER THREE: ENGINEERING GEOLOGICAL INVESTIGATION OF THE QUEENSTOWN URBAN AREA

3.1 Introduction

This chapter discusses the engineering geological investigation of the Queenstown urban area. The map produced from this investigation forms the basis for the adopted approach to identifying physical constraints to development.

The principal objective of the investigation was to describe the nature and distribution of the foundation materials and their relationships to one another. Thus producing an engineering geological database for use as a basis for identifying those surface and subsurface features which control site conditions, and therefore affect residential landuse options. The ultimate objective has been to produce a zonation map which indicates the type of physical constraint for a given area, and the degree to which it affects residential development.

3.1.1 Data Presentation

The option of using a computer-based graphics system, rather than the traditional overlay method, was chosen to deal with the potentially large amount of data that would be collected during the course of this investigation. It was proposed during the early stages of this study that there may be some advantage in using a Geographic Information System (GIS) such as Facility Mapping System for AutoCAD (FMS/AC) (Facility Mapping System Inc. 1992). However, it was decided subsequently that the size and requirements of the study did not warrant using anything more than a basic graphics program.

The 1:10,000 topographical base map, providing the base for field mapping and collation of data, was produced by digitally scanning the relevant portions of DOSLI 1:25,000 topographic sheets (NZMS 270, sheets F41C and E41D). The resulting raster file was converted into vector drawing using "Tracer for Auto CAD", version 1.0 (Hitachi Software Engineering Co Ltd., Copyright 1992). The overlay data (geology, geomorphology, roads, etc) was added to the system by manual digitisation using a Summagraphics Microgrid v.1.1 digitiser, Series III, Model 3648 (Summagraphics Corporation 1991). All data was edited using Autocad (Release 12.0, Autodesk 1992) graphics system.

The information is presented in two maps (map pocket) - the Engineering Geology Map (Figure 5, and cross sections Figure 6) which shows the nature and distribution of both foundation materials and geomorphic surfaces, and the Engineering Data Sheet (Figure 7) which shows limited cultural information, sampling sites, and the locations of previous engineering geological investigations.

Given the primary objectives of the investigation, the information presented on the Engineering Geology Map and within the text is designed for use as a guide to expected foundation conditions, and as such is not intended as a substitute for site specific investigations. Because only a small percentage of the study area has subsurface exposure, material distribution is based largely on inference from geomorphologic features. As a result, the map produced is to a certain degree interpretive. Some caution is therefore necessary in using this map.

3.2 Investigation Methodology

3.2.1 Existing Data

A large number of engineering geological and geotechnical investigations have been carried out by consulting engineers and engineering geologists in the Queenstown urban area as part of individual building site or subdivision investigations. The site-specific reports produced include any of the following: engineering geological description of materials (possibly including an interpretation of deposition mode); data on geotechnical properties of the materials (plasticity, shear strength parameters, and permeability for example); an assessment of suitability as foundation material; engineering geological plans and cross sections (at scales between 1:50 to 1:1,000); logs of test pits, auger holes, bore holes, and other exposures. A list of the reports made available to this study is given in Appendix C, and the locations of the relevant site investigations are shown on Figure 7 (map pocket).

3.2.2 Field Investigations

Initial (primarily geomorphological) data was gained by way of stereographic analysis of aerial photographs, followed by engineering geological field mapping. Some areas were inaccessible due to topography, dense vegetation or landowner constraints, but all major features were verified in the field. Exposure of materials was provided by way of road cuttings, foundation excavations, and stream- and lake-cut banks. Descriptions of materials were taken following the scheme of Bell and Pettinga (1983) but slightly modified (Appendix B).

A limited number of bulk (disturbed) soil samples taken from sites selected as "representative" of material type. These were described as above, and photographed where possible. Problems encountered during sampling included the very compact nature of some materials (especially the tills) which made removal very difficult when using the traditional method of geological hammer and spade, and the inaccessibility of the material (due to the height of the exposure in a cliff for example).

3.2.3 Laboratory Investigations

Grain size distributions were determined for twenty bulk samples taken from sites within the study area. The methods used followed the Standards Association of New Zealand NZS 4402 for soil testing. Wet sieving was carried out to separate the coarse fraction of each sample, and the fine fraction was dry sieved. No further analysis was carried out on the fine fraction. The results are presented in Appendix D.

3.3 Materials and Properties

The following section summarises the distribution, description and basic engineering properties of each of the units mapped as part of the investigation. This is intended as an indication of expected foundation conditions, and does not supersede detailed site analysis.

3.3.1 Schist Bedrock

(A) ***Distribution and Description***

The entire study area is underlain by pelitic and psammitic quartzofeldspathic greyschist and minor greenschist. One band of greenschist has been identified in the area, exposed in cut batters in the Queenstown-Frankton highway, and in outcrop on the lake shore below.

The lithology and texture of the greyschist within the study area is variable. It can change between "massive" or coarsely foliated psammitic schist, to finely foliated pelitic schist across short distances. The foliation attitude is also variable across the area, being planar to slightly wavy to tightly folded. Localised areas of complexly folded schist have been also been reported (Bell 1980a&b). Several well defined joint sets are recognisable, with spacing varying from very close to moderately close.

Apart from some iron staining along rock mass defects, weathering effects are restricted to the upper 0.5 to 1.0m of the bedrock profile, and to insitu rock adjacent to crush/fault zones within the schist. The shallow weathering profile is inferred to be the result of extensive erosion of the bedrock by ice, resulting in a relatively fresh surface. Defects within the weathered zone are often open, presumably in response to stress redistribution following the retreat of the ice mass, and to recent weathering processes.

Foliation shear zones within the rock mass are relatively common. Generally less than 100mm thick, these are clayey silt or silty clay seams of crushed schist that have developed parallel to foliation during tectonic deformation. As well as having a low shear strength, foliation shear zones are a control on subsurface hydrology as they form a relatively impermeable barrier to groundwater movement. Bell (1985c&d) recorded several foliation shear zones up to 100mm thick from exposures in the Frankton Road area, and numerous examples were noted during the field investigations for this study (although not mappable at this scale). Foliation shear zones are to be expected within the rock mass anywhere in the study area.

Several linear shattered and crushed schist zones occur within the study area. Crush zones commonly consist of slightly to highly weathered schist fragments set in a matrix of light to dark grey crushed schist pug and are often associated with groundwater seepages. Bell (1985d) mapped a 3m wide crush zone trending SE-NW across the lower slope of Frankton Arm, and a 120m wide zone of crushed and intensely folded schist was discovered during investigations for the Fernhill subdivision, trending N-S across Caples

Place (Bell 1980c). Both are overlain by undisturbed till, and are not considered active (Bell 1980c, 1985c). The Goldfield Heights road has exposed a 2.5m wide subvertical zone of highly jointed to shattered greyschist, trending NW -SE (Figure 30). It contains several thin layers of crushed schist and there is an area of groundwater seepage associated with this shattered zone. Several pronounced lineations can be identified from aerial photographs trending east-west across the southwestern end of Queenstown Hill. These features are inferred to represent the degraded traces of further crush zones. Exposed in a small water course in the steep schist cliff above Gorge Road is a two metre wide zone of highly deformed schist consisting of 0.5m of crushed rock and 1.5m of intensely folded and shattered rock bounded by slightly disturbed schist. On the upper slopes the features were degraded and revegetated, and although there was often schist outcropping to either side, there were no exposures found within the zones.

(B) *Engineering Properties*

Intact fresh schist rock material can provide more than adequate strength for house foundations and roading requirements. Bell (1980a) estimated the shear strength of finely laminated quartzofeldspathic greyschist to be at least 20 MPa parallel to foliation. Although the rock mass is typically weakened by various defects, namely clay-filled foliation shears, crush and shatter zones, joint sets, and a shallow zone of weathering, this is unlikely to be a significant problem for residential development.

Problems most likely to be encountered during excavation and construction include wedge and/or planar block slides, and rock falls and/or topples controlled by intersecting foliation and defect planes. Extensive zones of crushed and shattered schist will constitute relatively weak areas of foundations. the presence of groundwater seepages can cause a variety of secondary problems, including the erosion of exposed crush zones.

Figure 30: A 2.5m wide subvertical shatter/crush zone in psammitic greyschist, Goldfield Height road. View is approximately to the northwest along the trend of the zone. Note; very closely jointed to shattered rock on left side of zone, is more crushed towards the right. Also note that exposure is wet from seepages.

3.3.2 Sandy and Silty Tills

(A) ***Distribution and description***

Two distinct till deposits are recognisable in the Queenstown area - a silty gravel, and an overlying sandy gravel. Both tills occur as a veneer over bedrock, typically less than 1 to about 5 metres thick, particularly on the lower to mid hill slopes in the area, and in localised exposures underlying younger deposits. The sandy till averages a thickness of 1-2m. The silty till has only been exposed in a few excavations, and is inferred to be present below the sandy till only where combined till thicknesses exceed two metres. The two tills are not considered to be distinctly mappable units due to limited exposure of the silty till.

The sandy till generally consists of massive, sandy fine to coarse gravels to gravelly sands, characterised by their very compact, chaotic nature and high content of greywacke clasts (Figures 31-35). Occasional lenses of sorted sands are found within the unit. Five bulk samples of the sandy till were taken from locations around Queenstown and grainsize distributions determined (Appendix D). The silt and clay content for each ranged between 1.0 and 14.2%; sand content between 25 and 50%; and gravel content between 50 and 65% with minor cobbles. These results are comparable to grainsize distributions calculated by Bell (1980b) for similar material. In addition, Bell (1980b) determined the clay content of samples of sandy till from Fernhill to be generally less than 3%. In outcrop, the sandy till is further characterised by a medium to dark orangey brown (brownish orange) weathered (MW) horizon about 0.5-1.0m deep (Figures 31 & 34). Bell (1980b) showed by sampling and grain size analysis that this weathered zone has a slightly higher clay content.

Exposures of silty till are few (Figure 36). Only two bulk samples were taken from the silty till for grainsize analysis, and therefore the results are indicative only. Analysis showed the sand and gravel contents to be between 30-50% each, with greater than 20%

SAMPLE: A1 **LOCATION:** Antrim St, Queenstown

DESCRIPTION:
Medium brownish orange to orangey brown; SW-MW; moist; compact; massive; poorly sorted; chaotic; medium to coarse sandy fine to medium GRAVEL, with occasional cobbles and minor silt. Clasts predominantly subangular to subrounded schist, with abundant rounded greywacke. Upper 1 metre highly Fe stained.

INTERPRETATION:
Sandy till.

GRAIN SIZE DISTRIBUTION:

% Gravel: 58.8 **% Sand:** 34.7 **% Mud:** 6.5

Figure 31: Engineering geological description of Sample A1

SAMPLE: B **LOCATION:** Two Mile Creek, near Wynyard Crescent, Fernhill

DESCRIPTION:
Medium brownish orange to orangey brown; SW-MW; moist; very compact; massive; poorly sorted; chaotic; fine to medium sandy fine to medium GRAVEL, with some silt, occasional cobbles. Clasts predominantly subangular to subrounded schist, with abundant rounded greywacke.

INTERPRETATION:
Sandy till.

GRAIN SIZE DISTRIBUTION:

% Gravel: 55.4 **% Sand:** 30.4 **% Mud:** 14.2

Figure 32: Engineering geological description of Sample B

SAMPLE: P **LOCATION:** Queenstown Hill walking track

DESCRIPTION:
Medium brownish orange to orangey brown; SW-MW; very compact; massive; poorly sorted; fine to coarse sandy medium GRAVEL, with some pebbles to cobbles, minor silt. Clasts predominantly subangular to subrounded schist, abundant rounded greywacke. Contains occasional thin, sorted fines-depleted lense.

INTERPRETATION:
Sandy till

GRAIN SIZE DISTRIBUTION:

% Gravel: 64.7 **% Sand:** 25.9 **% Mud:** 9.4

Figure 33: Engineering geological description of Sample P

SAMPLE: L **LOCATION:** Hallenstein St, Queenstown

DESCRIPTION:
Medium orangey brown to brownish orange; SW-MW; moist; compact; massive; poorly sorted; fine to coarse sandy fine to coarse GRAVEL, with minor cobles, trace silt. Clasts predominantly subangular to subrounded schist, abundant rounded greywacke and quartz. Larger clasts generally flat-lying.

INTERPRETATION:
Sandy till.

GRAIN SIZE DISTRIBUTION:

% Gravel: 50.6 **% Sand:** 48.4 **% Mud:** 1.0

Figure 34: Engineering geological description of Sample L

SAMPLE: N **LOCATION:** Edgar Street, Queenstown

DESCRIPTION:
Light grey; SW; dry; compact; coarsely layered, subhorizontal; poorly sorted; medium to coarse sandy medium to coarse GRAVEL, with occasional cobble, trace silt. Clasts predominantly subangular to subrounded schist, abundant rounded greywacke.
Is overlain by sandy till

INTERPRETATION:
Glaciomarginal, below sandy till

GRAIN SIZE DISTRIBUTION:
% Gravel: 67.5 **% Sand:** 31.2 **% Mud:** 1.3

Figure 35: Engineering geological description of Sample N

SAMPLE: A2 **LOCATION:** Antrim St, Queenstown

DESCRIPTION:
1.5m below sample A1
Medium grey; SW; moist; very compact; massive; poorly sorted; chaotic; silty fine sandy fine to medium GRAVEL, with minor pebbles. Clasts predominantly subangular to subrounded schist, with abundant rounded greywacke.

INTERPRETATION:
Silty till.

GRAIN SIZE DISTRIBUTION:

% Gravel: 46.1 **% Sand:** 31.1 **% Mud:** 22.8

Figure 36: Engineering geological description of Sample A2

combined silt and clay (Appendix D). Bell (1980b) determined an average silt content of 39% and a clay content of 5.6% for samples of the silty till from Fernhill.

The silty till is interpreted as basal till deposited sometime during the later stages of the Otiran Glaciation. The overlying sandy till is interpreted as an ablation till deposited during the final ice retreat stages of the Otiran Glaciation. Occasional lenses of sorted sands and fine gravels occur between the two tills (Bell 1980b) suggesting water sorting during ablation.

(B) ***Engineering Properties***

Both the sandy and silty tills are generally dry to moist in outcrop. Average water contents determined by Bell (1980b) were 16% and 10% respectively. Groundwater seepages have been associated with the base of the weathered horizon in the sandy till, and with the lenses of relatively permeable sorted sands and fine gravels that occur within and between the two till units (Bell 1980b&c, 1982). Cohesion values are low to negligible due to the low clay content (Bell 1980b), and both tills suffer a significant loss of shear strength on void saturation (Bell 1980d). The sandy till is non-plastic except within the weathered horizon, which is slightly plastic in the Fernhill area (Bell 1980b&c, 1982). The silty till is very slightly plastic (Bell 1982).

Except where seepages or weathered zones have been encountered, both tills have been found to provide adequate bearing capacity (in excess of 100kPa), and are generally suitable for house foundation material (eg Bell 1980a & 1989; Duffill, Watts and King 1989; Royds Consulting 17859, 7602). Problems are likely to be encountered only if the material becomes saturated, particularly silty till, but such problems can be avoided by following normal site drainage procedures.

3.3.3 Fan-delta Complexes and the Shotover Delta

(A) ***Distribution and description***

High level fan-delta complexes, built out into the "Greater" Lake Wakatipu, have been preserved along the shores of the Frankton Arm, and between Sunshine Bay and the Queenstown town centre. The most prominent are the Marina Heights, One Mile Creek and Two mile Creek fan-delta complexes, all of which formed at the 340-350m asl lake level. They are of variable thicknesses, and may overlie bedrock, till deposits, and/or lake sediments.

Fan-delta deposits have been described as part of site investigations by Bell (1985b, 1985c, 1985d, 1989b), and others (DWK Lake Esplanade, RC 7306).

The grainsize distributions of the fan-delta complexes are, by nature of the deposits, variable. The mapped deposits consist generally of loose to compact, interlayered sandy gravels, gravelly sands, and sands (Figures 37-42), and may include silt lenses that represent the transition to lake bottom sediments. Layering is fine to coarse, gently to moderately inclined towards the lake, and may contain internal crossbedding and clast imbrication. The gravels are predominantly schistose, with minor greywacke reworked from till deposits. Grainsize distributions were determined for four bulk samples and showed the silt and clay content to be less than 3%, with sand content 18-39%, and gravel content 60-80% (Appendix D).

(B) ***Engineering Properties***

Water contents of 25-32% have been determined for sand and silt layers within the fan-delta gravels (Bell 1989b), but on the whole the gravels are expected to be moderately to highly permeable. Seepages have been noted within the gravels where groundwater flow has been inhibited by silt layers (Bell 1989b), but groundwater is not expected to be a problem given adequate site drainage. The loose, free-running nature of some of the gravels may present a minor stability problem in excavations, but the deposits are

SAMPLE: C **LOCATION:** Dart Place, Fernhill

DESCRIPTION:
Medium brownish grey; SW; moist; very compact; massive; poorly sorted; silty fine SAND, with some fine to medium gravel, rare cobble. Clasts predominantly subangular schist, minor rounded greywacke.

INTERPRETATION:
Fan-delta

GRAIN SIZE DISTRIBUTION:

% Gravel: 17.5 **% Sand:** 53.6 **% Mud:** 28.9

Figure 37: Engineering geological description of Sample C

SAMPLE: D **LOCATION:** Two Mile Creek, Queenstown-Glenorchy Road

DESCRIPTION:
Medium greyish brown; SW; moist; compact; faintly to coarsely layered, subhorizontal to gently inclined; poorly to well sorted; medium to coarse GRAVEL, with some sand, occasional cobble, trace silt. Clasts predominantly angular to subangular schist and quartz, occasional rounded greywacke.

INTERPRETATION:
Fan-delta.

GRAIN SIZE DISTRIBUTION:

% Gravel: 79.8 **% Sand:** 18.3 **% Mud:** 1.9

Figure 38: Engineering geological description of Sample D

SAMPLE: E **LOCATION:** Fernhill Road

DESCRIPTION:
Medium brownish grey; SW; moist; compact; slightly bedded to coarsely layered, gently inclined; poorly to moderately well sorted; coarse sandy medium to coarse GRAVEL, with occasional cobble, trace silt. Clasts predominantly subangular greyschist, minor rounded greywacke.

INTERPRETATION:
Fan-delta.

GRAIN SIZE DISTRIBUTION:

% Gravel: 69.2 **% Sand:** 29.5 **% Mud:** 1.3

Figure 39: Engineering geological description of Sample E

SAMPLE: F **LOCATION:** St Omer Courts, Queenstown.

DESCRIPTION:
Medium greyish brown; SW; moist; compact; slightly bedded, gently inclined; poorly to moderately well sorted; sandy fine to coarse GRAVEL, with trace silt. Clasts predominantly subangular to subrounded schist and quartz, minor rounded greywacke.
Outcrop contains lenses of cobbly sand, sand, and gravel.

INTERPRETATION:
Fan-delta

GRAIN SIZE DISTRIBUTION:

% Gravel: 59.5 **% Sand:** 38.6 **% Mud:** 1.9

Figure 40: Engineering geological description of Sample F

SAMPLE: M **LOCATION:** Beetham Street, Queenstown

DESCRIPTION:
Light orangey grey; SW-MW; dry to moist; hard; slightly to coarsely layered, gently inclined; poorly sorted; fine to medium gravelly fine to coarse SAND, with trace silt, rare cobble. Clasts predominantly subangular to subrounded schist and quartz, abundant rounded quartz and greywacke. Contains occasional thin layer of fine sand.

INTERPRETATION:
Deltaic

GRAIN SIZE DISTRIBUTION:

% Gravel: 39.0 **% Sand:** 56.7 **% Mud:** 4.3

Figure 41: Engineering geological description of Sample M

SAMPLE: K1 **LOCATION:** State Highway 6, north of Kawarau Falls Dam

DESCRIPTION:
Medium greyish brown to orangey brown; SW; dry to moist; coarsely layered, gently inclined; poorly to moderately well sorted; fine to coarse sandy fine to medium GRAVEL, with trace silt. Clasts predominantly subangular schist, occasional rounded greywacke.
Contains thin to thick lenses of fine sand (Sample K2)

INTERPRETATION:
Deltaic gravels

GRAIN SIZE DISTRIBUTION:

% Gravel: 60.7 **% Sand:** 28.7 **% Mud:** 2.8

SAMPLE: K2 **LOCATION:** State Highway 6, north of Kawarau Falls Dam

DESCRIPTION:
Medium brownish grey; SW; dry to moist; massive; well sorted; very fine to fine SAND, with some silt.
Represents lenses contained within sandy gravel (Sample K1)

INTERPRETATION:
Sandy lenses within deltaic - beach gravels

GRAIN SIZE DISTRIBUTION:

% Gravel: 0 **% Sand:** 80.5 **% Mud:** 19.5

Figure 42: Engineering geological description of Samples K1 & K2

generally interpreted as being stable. Bell (1989b) discusses the investigation of an eight metre high cut face in fan-delta sediments which remained stable at an angle of 65° for eight months before a suitable retaining wall was constructed (to control long-term "fretting"). With the exception of possible soft sand and silt lenses, the fan-delta deposits are expected to provide adequate foundations for residential development (Bell 1985d). Adequate provisions must be made for site drainage.

3.3.4 Beach Gravels and Sands

(A) ***Distribution and description***

The most extensive deposits of beach gravels and sands in the Queenstown area occur on the Kelvin Heights Peninsula, at Frankton and around Queenstown Bay on wave cut benches corresponding to various high lake levels (+6, +15, +25, and +45m).

The beach deposits generally consist of slightly to moderately weathered, loose to compact, dry, bedded, poorly to moderately well sorted, medium to coarse gravels, sandy fine to medium gravels, gravelly sands and sands (Figures 43 & 44). Grainsize distribution analysis of three bulk samples show that the gravel content of each ranges between 44 and 62%, sand content between 35 and 55% and very low combined silt and clay contents between 1.1 and 3.1%.

(B) ***Engineering Properties***

Investigations at sites in Queenstown have found that the beach gravel deposits have a bearing capacity in excess of 100kPa at less than one metre depth, providing that no lacustrine silts are present (RC 92169, 7272). The gravels are free-draining, usually dry, and no seepages have been associated with them. Due to their often loose, "free-running" nature, some of the gravels have the potential to cause problems in excavations. The angle of repose has been estimated at $\phi = 30°$ for gravels, and $\phi = 35°$ for sandy gravels (RC 7309).

SAMPLE: H **LOCATION:** Peninsula Road, Kelvin Heights

DESCRIPTION:
Light orangey brown; SW; dry to moist; compact to loose; finely to coarsely layered, gently inclined; poorly to well sorted; sandy fine to medium GRAVEL, with occasional cobble, trace silt. Clasts predominantly subrounded schist and quartz, occasional rounded greywacke. Clasts slightly imbricated.

INTERPRETATION:
Beach.

GRAIN SIZE DISTRIBUTION:

% Gravel: 61.9 **% Sand:** 35.0 **% Mud:** 3.1

Figure 43: Engineering geological description of Sample H

Figure 44: Layered fine to medium discoidal, imbricated beach gravels exposed in a foundation excavation near Remarkable Crescent, Frankton. The gravels are gently inclined towards the viewer.

3.3.5 Lacustrine Sands and Silts

(A) ***Distribution and description***

Laminated and massive lacustrine silts are exposed in road cuttings south of the Kawarau Falls (Figure 45), in the river bank north of the Falls, near Crystal Creek, and along Malaghan and York Streets in Queenstown. Boreholes near the Steamer wharf in Queenstown Bay showed silts are present there between 10 and 24m below present lake level (RC 92169). Massive, silty fine sands and moderately well sorted fine to medium sands are exposed adjacent to the Kelvin Heights Golf Course, and in road cuttings along Frankton Arm. These silts and sands are interpreted being fine grained sediment deposited in the lacustrine environment (some distance from the source) when the water level of Lake Wakatipu was much higher. From this supposition, and from the limited exposures, similar silts are expected to occur below and/or interlayered with fan-delta deposits, and below some beach deposits.

Grainsize analysis of laminated silt from near the present lake outlet showed the sample to consist of 90.4% silt and clay, and 9.6% sand. Massive silty sand from the Kelvin Heights golf course contained 63%sand, and 37% silt and clay (Appendix D).

(B) ***Engineering Properties***

Bell (1985c, 1985d) found silts near Crystal Creek to be plastic with a clay content between 30% and 50%. The insitu water content was above the plastic limit, and with increasing clay content the water content was approaching the liquid limit for the samples tested. There is a possibility of long term consolidation and differential settlement in such fine grained saturated sediments (Johnson and DeGraff 1988), and Bell (1985c) recommends specific foundation design. Silts investigated near Malaghan Street were found to be near saturation. Undisturbed peak effective strength was estimated to be $c' = 5$ kPa, residual $c' = 0$, and $\phi = 28°$ in both cases (DWK Malaghan St). Sandy silt exposed in York St was found to be very hard, and had a bearing capacity in excess of 100kPa (RC 7685).

SAMPLE: J **LOCATION:** State Highway 6, opposite Peninsula Road

DESCRIPTION:
Medium grey to orangey brown; SW; firm; finely laminated (varved), subhorizontal; SILT, with minor sand.

INTERPRETATION:
Lacustrine silt.

GRAIN SIZE DISTRIBUTION:

% Gravel: 0 **% Sand:** 9.6 **% Mud:** 90.4

Figure 45: Engineering geological description of Sample J

There is no evidence for deep seated failures in this area, but slope failures have been known to occur in similar material around Queenstown on slopes as low as 10° (DWK Malaghan St).

3.3.6 Alluvial Fans

(A) ***Distribution and Description***

Alluvial fans, dating from the latest glacial period to the present day, are present on the mid to lower slopes of the surrounding hills. Their distribution reflects, in part, the progressive lowering of the lake level. Only those fans that have been built out onto the present-day flood plains are considered to be presently (or potentially) actively aggrading. Those present at higher levels have been incised by their streams in response to the lowering base level, and are effectively stranded.

The most recent fans take the form of high angle, lobate features, and have built out from small, but periodically active, streams. The internal structure and texture of the fan deposits is variable. They generally consist of interlayered sandy gravels and sands, that become finer with increased distance from the source. The gravel is predominantly subangular to subrounded schist, with minor rounded greywacke reworked from till deposits. They contain occasional well sorted sand and gravel lenses, and occasional chaotic lenses of coarse angular schist gravels and boulders that are interpreted as representing episodic debris flow events. Bell (1980d) noted occasional silty lenses present in fans at Fernhill that he interpreted as loess deposition during periods of fan stability.

No samples were taken of alluvial material as part of this study.

(B) ***Engineering Properties***

The engineering properties of the alluvial fan deposits are likely to be similar to those of the fan-delta deposits. The likelihood of significant silt lenses is somewhat less. The deposits are expected to be generally well-draining. Local seepages are possible depending on the surface and subsurface drainage patterns. Any loose, free-running gravels could cause instability problems in excavations. They have been found to have adequate bearing capacity (RC 7234).

3.3.7 Fill

Areas of fill occur throughout the Queenstown area as a result of early mining activity, and more significantly as a result of urban development. They range from totally uncontrolled dumps of spoil to engineered placements of fill material, and as such vary in character and engineering properties. Adequately engineered fill should by design have satisfactory bearing capacity. Areas of fill are required to be registered with the council, and have not been mapped as a part of this study.

3.4 Slope Movement

The following section aims to describe the major examples of slope movement observed in the Queenstown Urban Area. Slope failures in the study area were mapped as part of the geological investigation. Assessment relied on aerial photographic analysis and a walkover survey. No site specific geotechnical or quantitative work was carried out on them.

3.4.1 Slope Failures in Bedrock

Five small landslides (less than 0.25km^2 each) have been identified on the slopes above Frankton Arm, between Marina Heights and Frankton (Figure 46). Classified as translational planar and wedge rock slides, these features are considered to be controlled primarily by foliation in weak schist (and possibly foliation shear zones although none were observed in outcrop). Insitu outcrops in the area expose kink-folded, thinly foliated, fissile, weak pelitic greyschist. Foliation is dipping 20-25° to the southwest, compare this to the debris slope angles dipping 20 to 30° also to the southwest.

Frankton No. 1 Slide - (Figure 47) major headscarp gently to moderately dipping down slope, some open cracks on head slope. Minor head scarps (some developed behind main scarp), are poorly developed (not broken through soil cover, or have been revegetated). The slide mass is characterised by subdued hummocky topography sub parallel to foliation. Exposures of weak pelitic schist in track cuttings. All suggests major control is foliation planes in weak schist (low tensile strength in head zone - pull apart under gravity down slope). Has been some back rotation and relaxation within slide mass.

In contrast, Frankton No. 2 and No. 3 Slides are characterised by steep, joint controlled head and lateral scarps. A large triangular, relatively intact, schist block forms the upper western part of the slide mass of the Frankton No.2 Slide. The western lateral scarp has formed along a member of a prominent continuous joint set dipping about 80° to the west (underhang). Minor collapse and rockfall is continuing along the exposed edge of this block, controlled by same joint set, dipping east and west. The head scarp of Frankton No.3 Slide has formed along joints dipping about 60° to the south. In places it is subvertical to overhanging (Figure 48). The head zones of both No.2 and No.3 are characterised by small to large angular schist blocks, and open "pull-apart" cracks. Schist blocks litter upper to mid body of slide mass, with fewer on the lower slopes/toe.

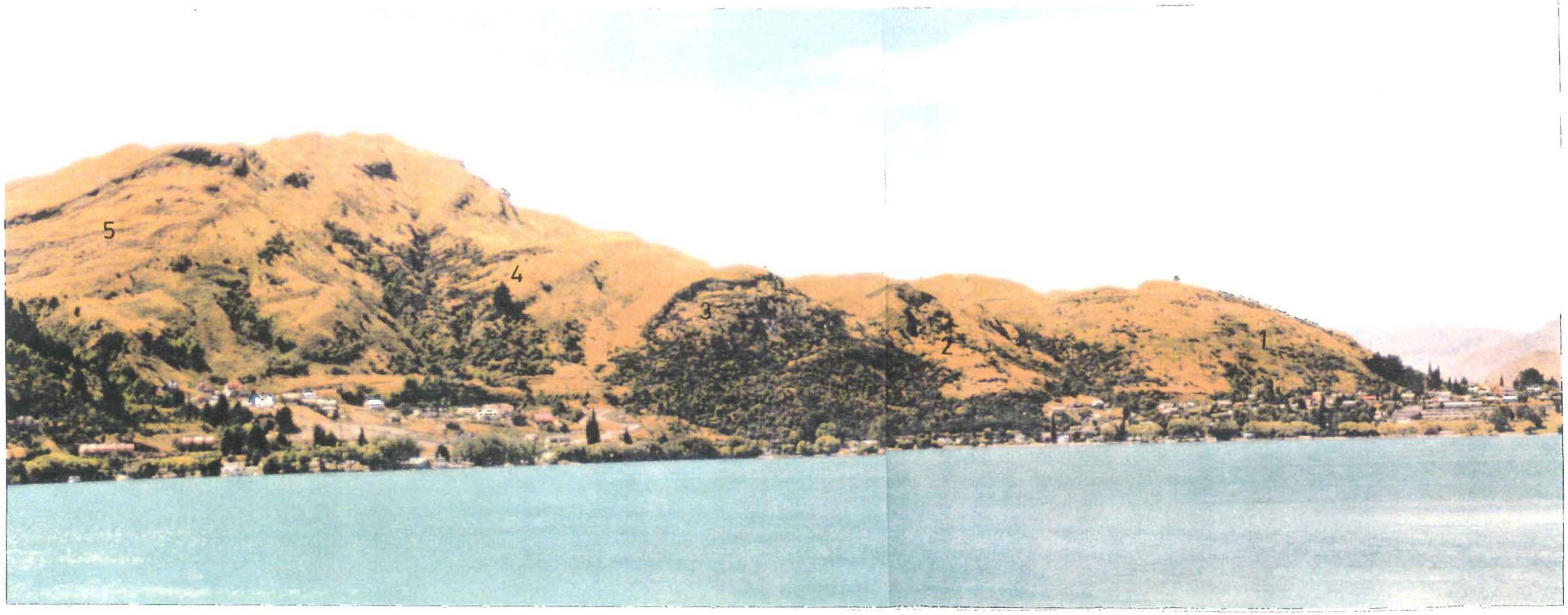

Figure 46: Bedrock slope failures above Marina Heights (on the left) and Frankton (to the right). Numbers 1 to 3 - Frankton No 1 to No 3 slides, 4 and 5 - Marina Heights slide No.s 1 and 2.

Figure 47: Frankton No. 1 slide. Note the poorly developed head scarp, and the very subdued degraded topography. No evidence of slide mass reactivation following the cutting of the track.

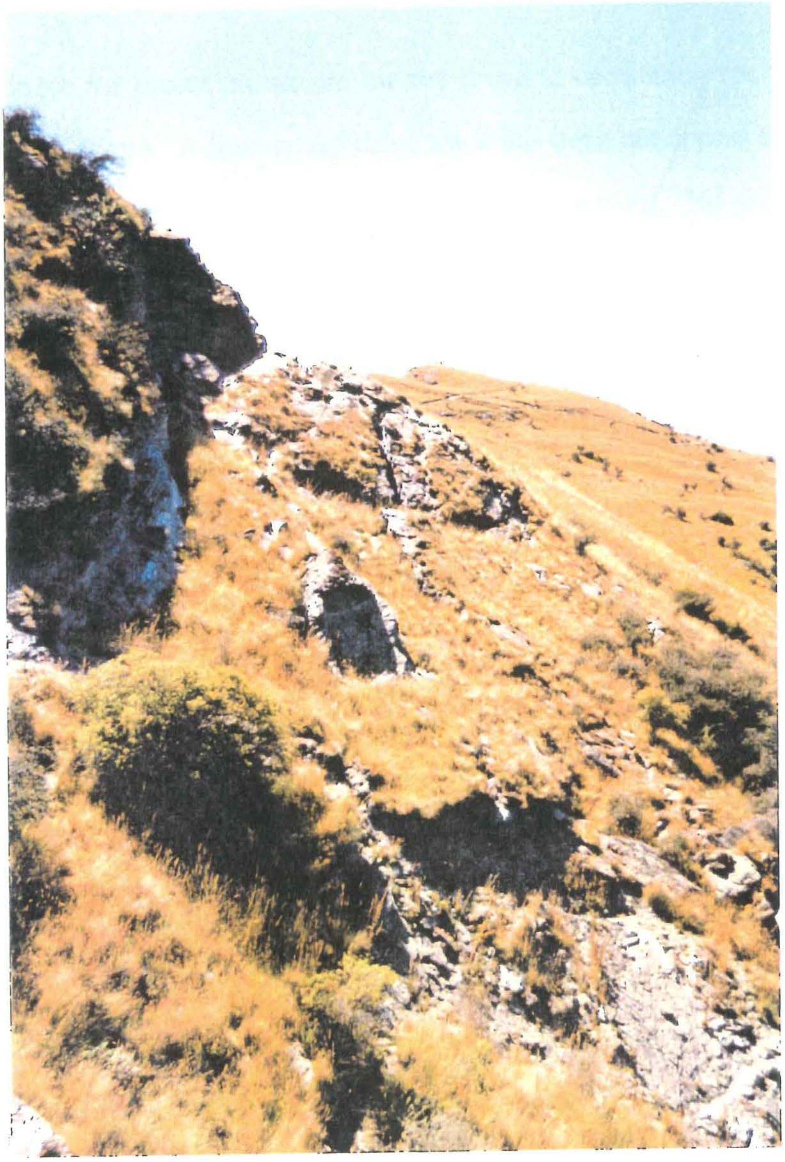

Figure 48: Frankton No. 3 Slide. Note sub-vertical headscarp, the blocky nature of the detached material, and the relaxation and the downslope breakup of the slide blocks.

The lower slopes of all three have developed into debris slides, with the toes apparently overlying deltaic surfaces.

There is no evidence for recent movement on any (beyond continuing rock falls/topples etc from degrading scarps). A four-wheel-drive track has been cut across slide mass and scarps of No.1 Slide with apparently no reactivation or movement. No sign of tilting of power poles placed on slide mass. No fresh scarps or cracks. And there are no fresh features on the other four slides.

The largest area of slope movement within the study area is the Queenstown Hill Slide (Figure 49), which covers approximately $2km^2$ extending from ridge crest to 2/3 downslope. Extents are inferred from geomorphology. The major head scarp is 3-4m high, and degraded (Figure 50). Several smaller scarps upslope are poorly developed and represent the retrogressing of the head zone. There are numerous secondary scarps within slide mass.

No schist is exposed in the head zone which is covered by a veneer of till. A prominent lateral scarp to the west has developed in schist, presumably controlled by a major joint set. There are several grabens and open cracks in the upper slopes west of lateral scarp, but the rest of slope morphology does not clearly show slope movement features. It is therefore presumed that the schist in this area has "relaxed" or been disturbed. The entire slide mass has subdued hummocky topography. Rare schist blocks littering the mid and lower slopes. Most recent movement probable southeastern portion of slide, but this area is still degraded. There is a possibility of very slow creep.

The Gondola Hill Slide was identified initially from stereo analysis of aerial photos that predate the establishment of dense exotic tree cover. Is an ancient degraded feature that appears to consist of two primarily translational rock slides or wedge failures that moved towards the south. Foliation in the area dips 20-25° to the southwest. The slope of the slide mass is about 23°. A number of angular schist blocks of various sizes litter the

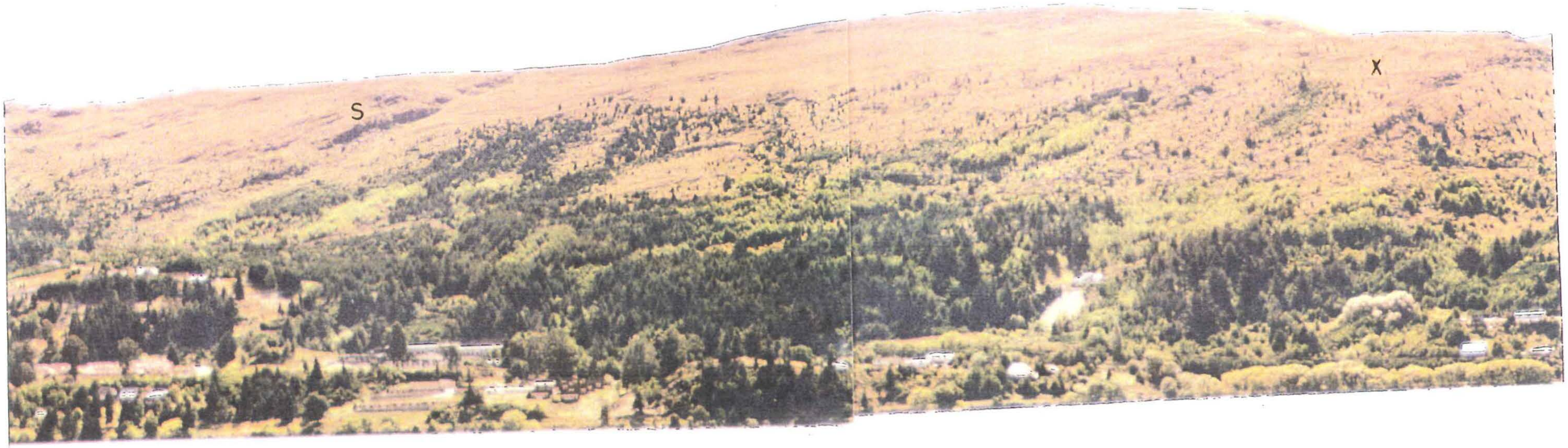

Figure 49: Queenstown Hill Landslide. The area of slope failure extends from the hill crest approximately to the dense exotic tree cover. Note the prominent lateral scarp to the left (S), and the zone inferred from geomorphology to have been the most recently active on the right (X). The bedrock beyond the left lateral scarp is relaxed to disturbed, with several wide open cracks in the head zone.

slope and bed of One Mile Creek. It is presumed that the controls are similar to those of other slides in the area. The position of toe extents is inferred by geomorphology,

One Mile Creek Slides adjacent to Gondola Hill Slides on southwest facing slopes (Figure 51). Large failures in bedrock are presumed to be foliation and joint controlled. The slide mass contains a series of reactivations. Scarps are largely littered with coarse angular schist fragments (debris/scree slides). There is a very prominent east lateral scarp. Subdued hummocky topography. Scarps generally revegetated except for small gravel slides.

Rock falls and topples may occur in steep slopes, bluffs, and cut faces with steeply inclined defects (primarily joints, pre-existing discontinuities). Initial fall may develop into roll or bounce, and boulders/pebbles can travel some considerable distance down slope. Identified areas of potential rockfall are the north slope of Peninsula Hill, steep bluffs above Gorge Road and below Gondola, and steep slopes anywhere especially with detached blocks already sitting there, high cut faces, and areas of landslide debris or colluvium. Result in accumulation of rock blocks/slabs on lower slopes and/or at foot (eg. Peninsula Hill).

3.4.2 Failure in Engineering Soils

No evidence for past slope failures in any surficial deposits were identified at the scale of this study, with the exception of a small earth slide <0.5m deep involving pedological soil (Figure 52). As mentioned in previous sections, both the sandy and the silty till are strong, competent, Are unlikely to undergo slope failure unless saturated and disturbed/excavated. Alluvial fan, deltaic and beach gravels are generally free-draining so pore water pressures not a problem. Loose, free-running nature of some of the gravels potential problem in excavations because of low angle of repose. Slumping of silt has been noted by others (DWK Malaghan St), but not during the course of this study.

Figure 50: Degraded head scarp (3 to 4m high) of the Queenstown Hill Landslide. View is towards the west.

Figure 51: Eastern extent of the One Mile Creek Landslide. Note the prominent east lateral scarp in the distance.

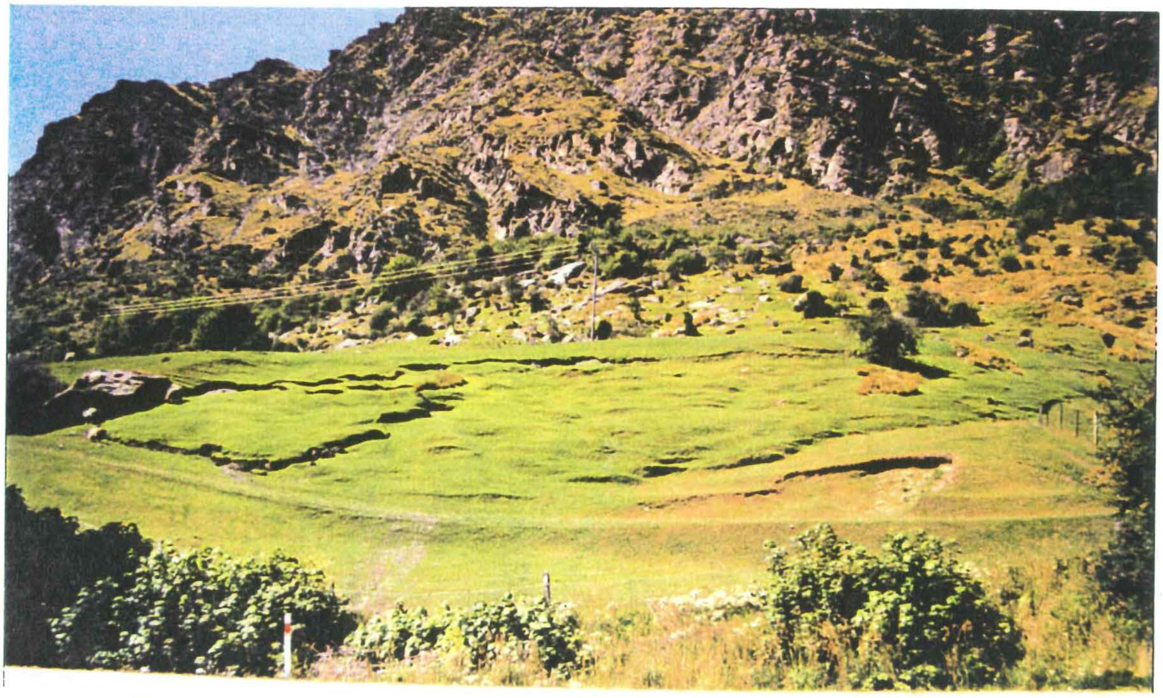

Figure 52: Earthslide in pedological soil following a period of high rainfall, February 1994, Gorge Road. Note the degraded, hummocky slope to the right representing the slide mass of past slope failures.

3.4.3 Implications for Development

Although areas of landslide debris are often able to support localised limited development (Coronet Peak Skifield, part of the Arthurs Point settlement), it would not be feasible to propose normal residential development.
Chaotic mix of clast and matrix supported debris, generally underconsolidated? Variable groundwater conditions can be expected.

3.5 Synthesis

- Basement rocks comprising pelitic and psammitic greyschist characterised by variable foliation and rock mass defects including foliation shear zones, shattered and crushed zones, and jointing.

- Two till units are recognisable: a compact sandy fine to coarse gravel to gravelly sand (ablation till) overlying a compact silty fine to medium gravel (basal till).

- Several fan-delta complexes, including the Shotover Delta, have been built out at a time when Lake Wakatipu was more extensive and had a higher water level than at present, and in general consist of interlayered sands and gravels with occasional silt lenses. Associated with the high lake levels is a series of high level beach terraces, and considerable lacustrine deposits of finely laminated or massive silts and fine sands.

- Fluvial deposits are not extensive. Several old high level, and presently active alluvial fans have been identified.

- There are numerous slope failures in bedrock in the study area. All are controlled primarily by foliation attitude relative to slope, and secondarily by foliation shear zones and joints. Trigger mechanisms are inferred to have been ice erosion and then stress redistribution following the unloading of the ice mass, and fluvial erosion of toe and slopes.

- Materials identified within the Queenstown urban area are generally more than capable of providing suitable foundations for residential development (with the exception of silt and fine sand units, loose gravels, fault zones within schist, and landslide debris), provided normal construction procedures are followed. Adequate drainage most important.

CHAPTER FOUR: LANDUSE PLANNING AND PHYSICAL CONSTRAINTS TO DEVELOPMENT

4.1 Introduction

This chapter describes the major types of physical processes and conditions that impose, or have the potential to impose, constraints to development in the Queenstown urban area. The basic principles of land use planning are discussed as is the application of engineering geology to the identification of physical constraints.

This study uses the terms "physical processes" (eg. slope movement, erosion, deposition) and "conditions" (eg. weak foundation materials), which lead to "physical constraints" to land use. The use of "hazard" and "risk" terminology, (variously defined by BSA 1979, IPENZ, Varnes 1984 and others) has been avoided. It is not the intention of this study to assess the magnitude of the physical processes or the probability of occurrance.

4.2 Principles of Land Use Planning

The purpose of land use planning is to identify characteristics of the land that render some areas more suitable for supporting certain human activity than others, and to guide development of the land appropriately. Such characteristics may include topography, geology, physical processes, and existing cultural features. Landuse suitability is usually determined or defined by considering the interactions between the physical characteristics of the area, the proposed development or use of the land, and the potential environmental effects (Lyle and Stutz 1987).

Varnes et al (1984) identified the three fundamental principles on which the assessment of physical constraints are based. These were identified in relation to slope movement processes, but are equally applicable to other physical processes and conditions:

(1) *The past and present are keys to the future -*

This assumes that physical processes in the future are most likely to occur under geological, hydrological and geomorphological conditions similar to those that have led to past and present activity (Varnes et al 1984). It does not, however, preclude further processes from affecting areas where they have not done so in the past, and may be invalidated by significant changes in the conditions of the past and present (Hutchinson in press).

(2) *The main conditions that can cause or aggravate physical processes are controlled by physical factors and are therefore identifiable.*

(3) *The degree of constraint can be estimated -*

(depending on the level of information gained in (2) above).

A fourth principle, applicable to this study, suggested by Hutchinson (in press) is that the various types of physical constraints can be recognised and classified.

4.3 The Identification of Geological Constraints

4.3.1 Application of Engineering Geology

The principal purposes of engineering geological investigations are to: (1) describe the physical nature and the distribution of the surface and subsurface geology, and geomorphology; (2) identify the physical processes affecting (and potentially affecting) the land; and to (3) evaluate the existing and potential geotechnical problems in the area (Bell and Pettinga 1986). The main application of the engineering geological approach is in providing an evaluation of the site conditions prior to development, usually during the feasibility stage of investigation (Bell and Pettinga 1986).

Engineering geology investigations typically follow a simple methodology involving stereographic analysis of aerial photographs, engineering geological mapping (at appropriate scales), logging of exposures of subsurface geology, and geotechnical testing of materials (Bell and Pettinga 1986).

Bell and Pettinga (1984) proposed under the old legislation that an engineering geological report be required for proposed developments, such that geological conditions be recognised as important to planning. Under such a proposal, the developer would be required to demonstrate that there are no physical constraints affecting the area in question or that they are able to be mitigated. Information presented in such a report would include: foundation material; surface and subsurface hydrology; topographic (geographical) and/or engineering constraints to development; and any "active" geomorphic processes with potential to affect proposed development (Bell and Pettinga 1984).

4.3.2 Terrain Classification Systems

Terrain evaluation is a joint geomorphological and engineering geological approach to the identification of physical constraints on landuse suitability (Hutchinson in press). It involves the initial compilation of an engineering geological database of the physical elements of the area such as geology, soil type, geomorphology, erosion and drainage, and the subsequent subdivision of the study area into parcels (terrain units) based on the similarity of physical characteristics.

The first step to the Geotechnical Area Studies Program (GASP) developed by the Hong Kong Geotechnical Control Office is the compilation and generation of a Terrain Classification Map (Table 3). From this inventory of physical data, several interpretive maps are derived (Figure 53). The most important being the Physical Constraints Map,

(a)

SLOPE GRADIENT	TERRAIN COMPONENT
0 - 5 deg	Hill crest or ridge
5 15	Sideslope - straight
15 - 30	concave
30 - 40	convex
40 - 60	Footslope - straight
60 <	concave
	convex
	Drainage plain (colluvium)
EROSION AND INSTABILITY	Floodplain
	Coastal plain
No appreciable erosion	Littoral zone
Sheet erosion - minor	Rock outcrop
moderate	Cut - straight
severe	concave
Gully erosion - minor	convex
moderate	Fill - straight
severe	concave
Well-defined recent landslip	convex
> 1 ha in size	General disturbed terrain
General instability - relict	Alluvial plain
recent	Reclamation
Coastal instability	Waterbodies - natural stream
	artificial channel
	water storage
	fish pond

(b)

SLOPE GRADIENT	TERRAIN MORPHOLOGY	SLOPE CONDITION
0 - 5 deg	Straight - insitu terrain	Cut: 0 - 5 m
5 15	Concave - insitu terrain	5 - 10 m
15 - 30	Convex - insitu terrain	10 - 20 m
30 - 40	Straight - colluvium	20 - 30 m
40 - 60	Concave - colluvium	30 < m
60 <	Convex - colluvium	Fill: 0 - 5 m
	Straight - < 2m thick colluvium	5 - 15 m
TERRAIN COMPONENT	Concave - < 2m colluvium	15 - 30 m
Hillcrest	Convex - < 2m colluvium	
Ridge	Straight - corestones on insitu	
Sideslope	Concave - corestones on insitu	
Footslope	Convex - corestones on insitu	**HYDROLOGY**
Drainage plain	Straight - alluvium	Inlet zone
Incised drainage channel	Concave - alluvium	Outlet zone
Disturbed terrain	Convex - alluvium	Water ponding area
Disturbed terrain/drainage	**EROSION AND INSTABILITY**	Subsurface flow
Rock exposure	No appreciable erosion	
Alluvial plain	Well-defined landslip - integral	
Floodplain	scar	
Coastal plain	debris	**VEGETATION**
Stream course (perenial)	General instability - colluvium	Grassland
Stream course with rock	insitu	Shrubland
exposure in bed (perennial)	Sheet erosion - minor (1 - 10% bare)	Mixed broadleaf woodland
Stream course with rock	moderate (10 - 40%)	Cultivated land
exposure in bed (ephemeral)	severe (40% <)	Non-vegetated - soil
Artificial channel (including	Rill erosion - minor	rock
catchwaters)	moderate	built upon
Water storage	severe	Reafforestation
Swamp/marsh	Gully erosion - minor	
Reclamation	moderate	
Beach	severe	
Dune	Highly jointed rock exposure or boulders	

Table 3: GASP classification schedules
(a) for Regional Studies (scale 1:20,000)
(b) for District Studies (scale 1:2,500)

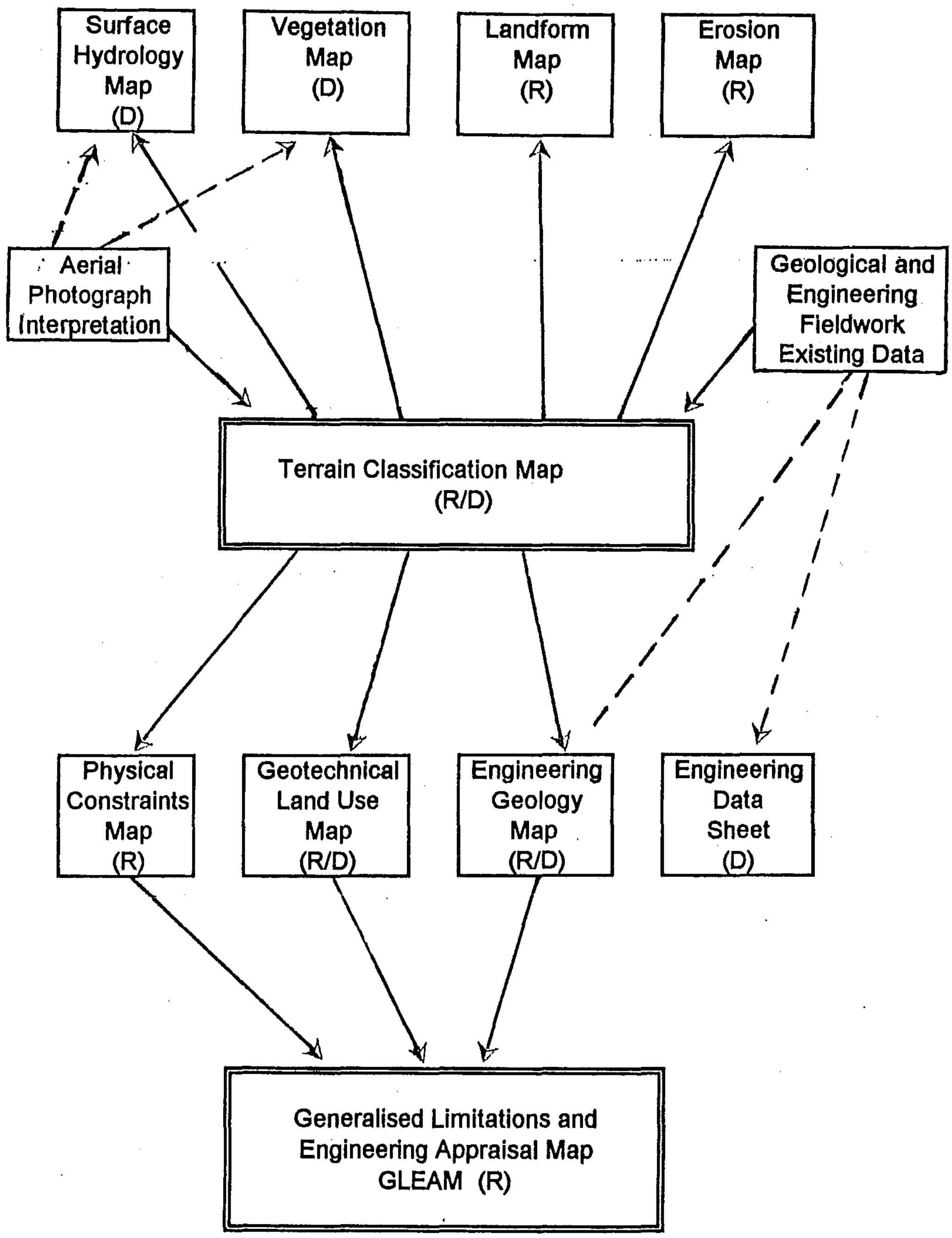

Figure 53: Maps derived from the Terrain Classification Map during GASP studies (from Brand 1988). Note: R = Regional study, D = District study.

the Geotechnical Land Use Map (GLUM), and the Generalised Limitations and Engineering Appraisal Map (GLEAM) (for further explanation refer to Brand et al 1982, Styles et al 1986, Brand 1988). These maps are of use to a variety of people - planners, engineers, and others.

Hutchinson (in press) considers the terrain evaluation approach to be one of the better techniques used for extrapolating surface and subsurface data. The provision of a classification schedule ensures that all relevant physical elements are considered, providing that the appropriate entities were chosen in the first place. It requires the careful choice of appropriate physical entities. However, it is to be noted that terrain evaluation methods are often based on the present landscape situation, and may neglect to consider the past and future evolution of the landscape (Hutchinson in press). For this method (or any other method) to be fully applicable to planning matters it must incorporate adequate identification of physical processes and geological limitations to land use and development, and should ideally be supported by representative geotechnical data (eg. case records) (Bell and Pettinga 1986, Hutchinson in press).

The terrain evaluation approach is only one with respect to landuse planning. Reviews of current practises can be found in Hutchinson (in press), and Brand (1988).

Another major type of map produced from an engineering geological inventory is the geological hazard map, which usually presents information on the type of hazards present in the study area, the degree of hazard (quantitative or qualitative), and includes recommendations on land use and management techniques (from an engineering geological viewpoint) (Gordon and Klousner 1986). Such assessments may cover the broad spectrum of physical processes (as terrain evaluation does), or concentrate on one process (hazard) only (eg Landslide Hazard Maps) (Varnes and Keaton 1984).

The first step in establishing any engineering geological inventory or assessment is to identify the potential user of the output information and the purpose of the study, and therefore identify what information is required and to what level of detail (and what scale). A widespread growth in the use of computers to store, manipulate and retrieve spatial data from the 1960's onwards (Coppock and Rhind 1991), and the development of Geographical Information Systems (GIS) has meant that more detailed data can be utilised, and more complex functions, comparisons, and manipulations can be done with the data (Varnes and Keaton 1984).

4.3.3 Existing Land Use Planning Systems in New Zealand

Bell (1987) reviews the physical processes, or geological hazards, that affect or have the potential to affect urban areas in New Zealand (Table 4). It is to be noted that while seismic and volcanic events have the potential to be catastrophically damaging and should be taken into consideration, the (usually) less severe but more frequently occurring processes such as flooding, erosion and slope instability are of more immediate importance to most urban areas in New Zealand (and are more readily avoided or mitigated)..

There are a number of major map series, listed in Table 5, covering parts or the whole of New Zealand that contain geological and geotechnical data of varying relevance to urban land use planning. Generally produced at scales of 1:25,000 or smaller, they are of use as guides for the broad indication of (selected) conditions, and cannot be (nor were they generally intended to be) used on their own for urban land use or development planning purposes.

To date, only one systematic, broadly applicable landuse planning or assessment scheme has been utilised in New Zealand, described below. Several specific regional and local landuse planning studies and physical constraint assessments have been undertaken in different parts of New Zealand, also described below.

HAZARD CLASSIFICATION	GEOTECHNICAL CAUSES	SCALE	FREQUENCY	COMMENTS
SETTLEMENT	A. Soil shrinkage and/or swelling	VS	N - E	Identifiable from soil characteristics; remedied by moisture control.
	B. Compaction and/or consolidation	VS - S (M?)	M - E	Identifiable from material properties; remedied by prior excavation of compressible gound, or by improved compaction of fill.
	C. Subsidence due to mining	VS - M	M - E	Predictable from mining records and empirical analytical methods; control difficult and expensive.
LANDSLIP	A. Rock or soil fall	VS (- S)	M	Potential problems identifiable by site inspection; various engineering solutions available.
	B. Shallow "regolith" failure	VS - S	M	Predictable from topography and regolith characteristics; control of infiltration and pore pressures of infiltration and pore pressures.
	C. Deep-seated landslide	VS - S (M?)	M - E	Existing landslide areas identifiable by engineering geological techniques; remedies depend on nature and scale of problem.
	D. Bedrock failure	S - M	L - M	Potential slope failures may be difficult to predict; remedies (if any) site specific.
	E. Cut and/or filled ground	VS - S	M - H	Predicted by geotechnical investigations; various engineering remedies available.
FLOODING	A. Storm events	S - L	M - H	Flooding problems in low-lying areas predictable from historic records; various remedies.
	B. Catchment or channel modification	S - L	M - H	Predictable from hydrological records or modelling; various engineering solutions.
	C. Dam failure or overtopping	M - L	L - M	Rare event given sound engineering design and construction.
EROSION	A. Storm events	(VS-) S (-M)	(L-) M (-H)	River-bank erosion often associated with flooding; coastal erosion may result from storm-wave attack; possible structural or channel modification solutions.
	B. Tsunamis	M - L	L (- M)	Rare large events with potential for widespread damage in coastal areas; early warning possible but only limited protection feasible.
	C. Channel or current changes	S - M (-L)	(L-) M (-H)	Natural or human-induced changes with readjustment of dynamic equilibrium; prediction and various remedies possible.
	D. "Internal" piping	VS (- S)	M - H	Occurs in certain fine-grained soils by dispersive or hydraulic piping, forming subsurface tunnels and/ or collapsed gullies; various geotechnical investigation and remedial methods.
SEISMICITY	A. Ground shaking	M - VL	L - M	Ground shaking accompanying earthquakes with potential for damage over large area; aseismic design and construction codes.
	B. Gound displacement	S - M	L - M	Scarp development (and associated ground warping) confined to fault traces; appropriate planning codes and/or building restrictions.

EXPLANATION: "Scale" represented by area likely to be affected by particular hazard, as follows: very small (VS) <100 sqm; small (S) 100-10000 sqm; medium 1000-1,000,000sqm; large 1-100 sqkm; very large >100 sqkm.

"Frequency" defined in terms of likely recurrence interval between damaging events, as follows: negligible (N) >1000yrs; low (L) 100-1000yrs; moderate (M) 10-100yrs high (H) 1-10 yrs; extreme (E) <1 yr.

Table 4: Major geological processes which may affect existing or proposed urban areas in New Zealand. (from Bell 1987)

MAP SERIES TITLE	TYPE OF DATA SHOWN	PUBLICATION SCALE	PUBL. DATES	COMMENTS
Geological Map of NZ 1:250,000	basic geology	1:250,000	1960 - 1968	Show time stratigraphic units; not designed for, and of limited value for detailed urban planning.
Geological Map of NZ 1:63,360 and 1:50,000	basic geology	1:50,000 & 1:63,360	1950 -	Same as above; best basis for special purpsoe and interpretive maps at present.
Late Quaternary Tectonic Maps	active faults, folds	1:50,000 & 1:63,360	1969 -	Indicate possible faulting hazard areas; some Quaternary geology in later maps; some have larger scale map inserts.
Geological Map of NZ Industrial Series	basic geology and geological hazards	1:25,000	1966 -	Show basic (1:63,360) geology; geol. hazards and some eng. geol. data provided. Limited coverage; good for preliminary local planning.
NZ Geological Survey Miscellaneous Series	basic geology	various	1969 -	Mainly basic geology, catering for miscellaneous areas and topics.
Soil Maps of NZ - several series 1:1,000 to 1:250,000	basic soil sets, series, types and phases	various	/	Data varied, applicable for broad assessments mainly; some valuable eng. prop. data on some maps, but generally too shallow for detailed planning of eng. or urban works.
Detailed Regolith, Geomorphology Maps	loess, tephra, surface deposits	1:30,000 & 1:250,000	1972 -	25 maps; show regolith and landform features.
National Resource Surveys	simplified basic geology	1:500,000	1959 - 1973	Limited factors incorporated, compiled from existing data; suitable only for broad plannling.
NZ Land Inventory Rock Types and Surface Deposits NZMS 290	rock types and resources; faults, rock hardness	1:10,000	1979 -	Map emphasis rock type and hardness, with data on geol. resources, active faults. Limitations due to lack of data, scale enlargement. Suitable only for broad planning. Despite title, surficial deosits not shown.
NZ Land Resource Inventory	multifactor on one map (rock type, soil, slope angle, erosion type and degree, vegetion classes	1:63,360	1975 - 1979	Limited factors, size of land units (60ha), scale enlargement, and limited range of physical and geological factors; limits use to broad planning; not suitable for
Rock Type and Resources Maps	basic geology, rock types	1:31,680 & 1:12,6720	1965 - 1976	As above

Table 5: Major map series presenting geological and geotechnically related data applicable to urban planning.
(from Hancox 1981)

(A) ***Urban Land Use Capability (ULUC) System - National Water and Soil Conservation Authority***

The ULUC system of assessing landuse suitability follows the terrain evaluation approach. The basis of this system is an inventory quantifying lithology, soil type, geomorphology, erosion, soil drainage, and land cover/use (Table 6). The main types of physical constraints to urban development are identified and ranked for each land parcel which is then given a ULUC Classification referring to the overall degree of constraint to development (Table 7). The final output is the ULUC Assessment Map, which is the basic planning tool derived from any ULUC survey. Broad types of landuse can be assigned to the ULUC assessment, but usually only as a guideline (Jessen 198&). A full description of the ULUC system is given in Jessen (1987). ULUC surveys have been carried out in a number of areas in New Zealand including Northland, Waikato, Greymouth and Otago. One was completed in Queenstown in 1988 (discussed in section 4.4.4)

An apparent weakness of the ULUC system mentioned by Horrey (1989) is that although the guidelines (Jessen 1987) suggest a ranges of scales that surveys can be conducted at, it includes only one classification schedule. Horrey (1989) interpreted this as the inability of the system to recognise the need for more detailed data at larger scales. It is to be noted however that the classification schedule is presented as a guide to what physical elements should be included, and that the details are left to the discretion of the surveyor, hence there is scope for the subdivision of elements at larger scales.

Another concern is that typical of terrain evaluation systems, the ULUC system classifies land mainly on the basis of geomorphology and surficial information. Followers of the system should ensure that sufficient attention is given to the engineering properties of the subsurface geology (geotechnical data), and to the identification of active, or potentially active, geological processes. Bell (1988b) questioned the relevance of several of the survey parameters (namely lithology, pedological soil units and land use/cover) to urban

1.	Rock (rock type)
2.	Soil (soil unit)
3.	Landform: (a) slope class (b) landform type
4.	Erosion: (a) erosion degree (b) erosion type (c) percentage area class (d) erosion development stage
5.	Drainage (soil drainage class)
6.	Land cover/use: (a) land cover (b) land use

$$\frac{\textit{rock — soil — landform}}{\textit{erosion — drainage — land cover/use}}$$

Table 6: The Urban Land Use Capability survey classification schedule (from Jessen 1987)

ULUC Class

The ULUC class defines the *overall degree of physical constraint which determines the land's capacity for urban development and sustained urban use.* Five classes are used: A, B, C, D and E. The overall degree of physical constraint is least in class A and most in class E land. Standard short definitions of the classes are as follows:

- **ULUC class A**—Land with negligible, or no, physical constraints to urban development and use.
- **ULUC class B**—Land with slight physical constraints to urban development and use.
- **ULUC class C**—Land with moderate physical constraints to urban development and use.
- **ULUC class D**—Land with severe physical constraints to urban development and use.
- **ULUC class E**—Land with physical constraints so severe that they essentially preclude any kind of urban land development.

Table 7: The Urban Land Use Classification (from Jessen 1987)

land use planning, and expressed doubt over the implied level of geotechnical evaluation claimed by the survey given that little geotechnical data is included in the ULUC surveys. Bell (1988b) also criticised the lack of clear objectives in the handbook, and the lack of guidelines to assist in using the system correctly,

(B) ***Regional Landslip Hazard Classification (RLHC) - Wellington Regional Council (1988)***

Locations of existing landslides (many the result of a storm event in 1976) and other landforms were identified and compared with slope angles derived from topographic contours. On the basis of landslip densities three relative potential landslip hazard classes were identified (applicable to bedrock only);

slope 0-4° - low hazard
5-15° - moderate hazard
>15° - high hazard

and two special classes, both low hazard, were identified for alluvium and human-modified areas. The classification includes recommendations on further engineering geological and geotechnical investigations required prior to development for each class, and mentions conditions or actions that would affect the degree of hazard (Kingsbury et al 1991). Due to the method of information collection (by aerial photograph interpretation onto a topographic base, field work done only to check model) the RLHC is only of use as guide on a regional scale, and is not intended to be site specific.

(C) ***Picton - Waikawa - Shakespeare Bay Hazard Assessment - Horrey (1989)***

Engineering geological investigations were carried out at scales of 1:5,000 and 1:10,000, and site specific investigations at larger scales, which identified six hazardous geological processes with the potential to affect the Picton, Waikawa and Shakespeare Bay urban areas. On the basis of this information, a hazard map was compiled at 1:5,000 showing the areas potentially at risk, the estimated associated degree of hazard using a four-fold classification system (Table 8), and the expected limitations to development (Table 9).

Horrey (1989) also compiled a Development Suitability Map at 1:10,000 based on the engineering geology and hazard maps which indicates the degree of geotechnical limitations to future development (Table 10). These maps are intended as a guide to expected foundation conditions and likely site investigation requirements, and as a tool for landuse planning and land management, and are not intended as a substitute for site specific investigations.

(D) ***Urban Geology Map of Nelson - NZ Geol Survey***

Intended as part of a series of maps,* the Urban Geology of Nelson sheet shows bedrock and surficial geology, and some engineering geological and geological process data (slope instability) at a scale of 1:25,000 (Hancox 1981, Bell 1987). It is suitable for local and site specific planning (Hancox 1981).

(E) ***Site Specific Engineering Geological Mapping - Various Authors***

Numerous site specific engineering geological investigations have been carried out throughout New Zealand, involving collation of existing data, field mapping and exposure logging - usually at scales between 1:50 and 1:2000 (Bell and Pettinga, 1983), the logging of any test pits, auger or bore holes, and geotechnical field and laboratory testing of materials (Table 11). Such investigations provide relatively detailed information on foundation conditions, and on active or potentially active geological processes that may affect the site.

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* Nelson sheet only one completed up to 1981, others in preparation (Hancox 1981)

DEGREE OF HAZARD	SLOPE MVT	FLOODING	DEBRIS DEP.	STR BANK EROSION	COASTAL EROSION	GROUND SUBSIDENCE
HIGH	Slope movements during the last 30yrs.	Areas liable to in undation in a 30yr period, assuming adequate performance of existing flood protection works.	Areas liable to debris deposition, siltation, and channel migration in a 30 yr period.	Sites of active removal of material at the stream bank within the last 30 yrs.	Sites of active removal of material at the shoreline within the last 30 yrs.	Areas of permanent ponded drainage. Potential ground subsidence hazard.
MOD	Slope movements showing no sign of activity during the last 30 yrs.	Areas liable to inundation in a 100 yr period, assuming adequate performance of existing flood protection works.	Areas liable to debris deposition, siltation, and channel migration in a 100 yr period.	Insufficient data available to assign low and moderate hazard		// //
LOW	Slope angle in excess of 15deg, with no history of slope movement identified.	Areas liable to inundation in an extreme flood event, assuming failure of flood protection works.	Areas liable to debris deposition, siltation, and channel migration in an extreme rainfall event.			// //
NEGLIGIBLE	Slope angle less than 15deg, with no history of slope movement identified.	No significant hazard.	No significant hazard.	No significant hazard.	No significant hazard.	No significant hazard.

TABLE 8: Hazard zone definitions for hazard mapping in the Waikawa area.
from Horrey (1989, p110)

DEGREE OF HAZARD	SLOPE MVT	FLOODING	DEBRIS DEP	STR. BANK EROSION	COASTAL EROSION	GROUND SUBSIDENCE
High	Extreme limitations Development not recommended.	Extreme limitations Development not recommended.	Extreme limitations Development not recommended.	Development not recommended without certified engineering design of streambank protection works	Development not recommended without certified engineering design of coastal protection works.	Unsuitable for development without site dewatering and filling. Further investigation of ground subsidence potential required.
Moderate	Significant limitations. Detailed site investigations required. Development may be possible on selected sites.	Significant limitations. Site investigation of flood hazard required Protective measures and special foundation design may be required.	Significant limitations. Site investigation of debris and siltation hazard required. Culvert and watercourse design critical.	Insufficient data available to assign low and moderate hazard		\\ \\ \\
Low	Some limitations. Engineering design of foundations and stormwater and effluent disposal required.	Some limitations. Generally favourable but some assessment of flood hazard may be required. Stormwater control important.	Some limitations. Generally favourable but some assessment of debris and siltation hazard may be required. Culvert and watercourse design important.			\\ \\ \\
Negligible	Suitable for residential development given normal engineering prudence, and compliance with local authority by-laws.					

TABLE 9: Development recommendations for the hazard zones defined in Table 8 from Horrey (1989,p111)

CLASS	CLASS DESCRIPTION
IV	Extreme geotechnical limitations, generally unsuitable for development
III	Moderate geotechnical limitations, suitable for development only after detailed geotechnical site investigations
II	Low geotechnical limitations, generally suitable for development, although some geotechnical investigations may be required
I	No significant geotechnical limitations, suitable for development

Table 10: Development Suitabilty Classes used by Horrey (1989)

Engineering Geology Investigation Objectives	Typical Map Scales	Geotechnical Data
1. Identification of "regional" hazards such as floodplains and "active" fault traces 2. Mapping of bedrock and surficial geology	1:100,000 ↓ 1:25,000	Characterisation of lithologies and identification of "problem" soil types; assessment of resources (e.g. aggregate availability and long-term requirements)
1. Engineering geological and/or pedological mapping, with limited excavation logging 2. Identification and investigation of "local" hazards (e.g. landslides)	1:10,000 ↓ 1:5,000	Geotechnical characterisation of mapping units as required for land-use zoning decisions; specific evaluation of tectonic and hydrologic hazards
1. Engineering geological site mapping and subsurface investigations 2. Interpretative risk assessment and/or planning guidelines	1:2,000 ↓ 1:1,000	Limited testing (e.g. plasticity/grainsize) to indicate general characteristics of site materials; hazard avoidance or mitigation measures
1. Detailed site investigation of specific areas identified at Concept Plan stage 2. Engineering geological mapping and logging to meet any "local" authority requirements	1:1,000 ↓ 1:500	Additional geotechnical testing to verify design and/or construction feasibility as required; investigation of specific features to facilitate stage E
1. Confirmation of mapped geology 2. Additional investigation as required	1:500 ↓ 1:50	Detailed investigations for design of cut and fill batters if required; control of earthworks
Engineering geological investigations only if required (A → E should prevent site "problems")	1:200 ↓ 1:50	Site specific testing for foundations if required; control of earthworks, drainage, etc

Table 11: Engineering geological input for urban planning in New Zealand (from Bell 1984)

4.4 Landuse Planning and Urban Development in the Wakatipu Basin

The Queenstown - Lakes District Council is at present in the final stages of preparing the Queenstown - Lakes District Plan (1994) as required by the Resource Management Act (1991). This is being done with the involvement of the Council, various consultants, the business community, and residents of the region. The District Plan shall replace the Lakes - Queenstown Wakatipu Combined District Scheme 1983, and shall be the principal planning document for the District over the next ten years.

4.4.1 The Resource Management Act 1991

Under the District Scheme 1983, land use and land development were controlled by zones that restricted activities on the basis of the type of activity itself (ie. development was controlled by way of schedules of permitted uses within specific zones). The principal aim of the zoning was to separate incompatible uses. Uses other than those specified for the particular zone required special consent from a planning committee. The objectives of the Scheme were predominantly concerned with the preservation of arable land, retention of high tourism value and expansion, and maintaining the standard of amenities and services for the community. Land identified as being suitable for residential development was subdivided into eight zones. Seven of these zones were defined primarily on the basis of ensuring user compatabiliy. Residential zone 4 however, was defined as the elevated areas between Queenstown and Frankton, above Fernhill and Sunshine Bay, and above Kawarau Falls. These areas were distinguished on the basis of topography alone, with the concept that "stringent controls are required to prevent development occuring on land which is potentially unstable and therefore unsuitable for residential development" (District Scheme p171). While this statement is limited in its recognition of factors resulting in slope instability, one requirement of the zone was that an engineering geology asssessment be made of any proposed development site.

Under the Resource Management Act 1991 however, landuse and activities are controlled by a policy based approach which governs on the basis of the perceived effects that any given the activity could have on the environment. The essence of the Act is contained in Section 5:

5(1) "The purpose of this Act is to promote the sustainable management of natural and physical resources."

5(2) "In this Act 'sustainable management' means managing the use, development, and protection of natural and physical resources in a way, or at a rate, which enables people and communities to provide for their social, economic, and cultural wellbeing and for their health and safety while - (a) Sustaining the potential of natural and physical resources (excluding minerals) to meet the reasonably foreseeable needs of future generations; and (b) Safeguarding the life supporting capacity of air, water, soil, and ecosystems; and (c) Avoiding, remedying or mitigating any adverse effects of activities on the environment"

While in effect there are no major changes from the previous legislation, there has been a consolidation and focus of objectives and policies. In particular, under the Act:

Land may not be subdivided unless there is a rule in the District Plan which allows it, or a resource consent has been granted [Section 11(1)]. Rules in the Plan may prohibit, regulate or allow activities, with regards to the actual or potential effect(s) on the environment [Section 76]. The territorial authority is obliged under the Act to disallow subdivision if it considers the land to be "unsuitable" [Section 406]. Where a subdivision consent is granted subject to a condition to be complied with on a continuing basis, the territorial authority is required to issue a consent notice specifying any such condition, which may be registered under the Land Transfer Act (1952), and bind all subsequent owners of the land [Section 221 (1) & (4)]. The subdivider may be required to demonstrate that the land will not be affected by "erosion, subsidence, slippage, or inundation from any source" [Section 220 (1)].

4.4.2 The Queenstown Lakes District Plan 1994

As the District Plan had not been publicly released in time for it to be included in this study, only those issues and recommendations discussed in the preparatory reports can be commented on here.

As part of the process, a number of studies have been commissioned by the Council to identify and address the main issues with regard to management of resources in the district and planning for the future. Of interest to this study are the Settlement Strategy Study prepared for the District Council by Constantine Planners Ltd (1993), and the Geology for Resources Management Planning Report prepared by Riddolls Consultants Ltd (1993).

The purpose of the Settlement Strategy Study was "to examine present provisions, preferences and predictions for settlement expansion within the District...to establish present and probable future constraints upon meeting settlement expansion needs; and to determine appropriate means of providing for settlement expansion in the district plan." (Constantine Planners Ltd 1993 p4). A number of factors important to development within the Wakatipu Basin were recognised, of which "Natural Hazards" is the only one with direct relevance to this study. The geology of the District and its relationship to natural hazards, and also to ground water and waste disposal, is discussed by Riddolls Consultants Ltd (1993).

On the basis of their study into the current settlement situation within the Basin and the expected demands, Constantine Planners Ltd (1993) identified several options for the direction that urban development could take in keeping with the principles of the Resource Management Act. They are:

1. Higher density development within existing settlements
2. Incremental growth responsive to market forces

3. Infilling and planned extension to existing settlements
4. New towns with populations of 2500 to 5000 people
5. Hamlets each comprising 10 to 50 small rural "lifestyle" units
6. Rural subdivision

The viability of each of these options is constrained by servicing capability, transport routes, visual impact, geology and physical processes.

4.4.3 Previous Hazard Assessment in Queenstown

Active proccesses and constraints have been identified at site level as part of engineering geological site investigations undertaken in various parts of Queenstown. The data gathered and the assessments/evaluations made are primarily held by the consulting engineers and engineering geologists involved, and hence the information is dispersed.

The Queenstown Urban Land Use Capability Study - Otago Catchment Board (1988)
In 1988 the Otago Catchment Board conducted an Urban Land Use Capability survey in Queenstown, which covered the area from Sunshine Bay to Frankton to Kelvin Heights. Land already developed was not included; the survey instead concentrating on undeveloped land zoned Residential 4.

The survey closely follows the guidelines of Jessen (1987). It covers 9 sheets plotted on aerial photo enlargements at a scale of approximately 1:6,000, and provides a physical description of the area using an alpha-numeric land resource inventoy. On the basis of the constraints identified, the area was subdivided into 220 ULUC map units. The ULUC Class was defined from the ranked physical constraints, and was shown on the map by a symbol to show the degree of physical constraint for each parcel of land and the three major types of constraints controlling degree. The ULUC Class for each land parcel is described in the appendix of the survey report, which also lists the constraints code, area, description of constraint(s) (eg watercourse, schist bluffs), and engineering design features (drainage, terracing, cut and fill, site specific design, unsuitable -hazards).

Bell (1988b) had a number of specific criticisms aimed at the the Queenstown ULUC Study:

1. There is no guide to the applications and limitations of the study.

1. The inventory map units are "unnecessarily complex" (p7) and may lead to the subdivision or groupng of land on parameters that are of minor significance to development suitability (eg vegetation density).

2 "The ULUC class units imply a level of geotechnical evaluation which has clearly not been carried out" (p7), and the constraint severity zoning show a poor understanding of the concepts involved. Therefore the constraint zoning is not always appropriate.

3. The survey does not define its use of hazards and risks, nor is the basis of the hazard/risk overlay discussed in the text.

4. The preface intimates that the Queenstown ULUC study can be used by the Council to evaluate development proposals and to grant consents or impose conditions. However the data presented is not sufficient to "override" engineering geology and geotechnical investigations, and is not suitable for the planning or control of subdivisions (Bell 1988b).

Bell (1988b) suggests however, that the Queenstown ULUC Study is of some use for defiining areas suitable for future residential development, and for identifying those areas that will require engineering geological and/or full geotechnical investigations during subdivision. But that it should only be used at regional to district levels (1:100,000 to 1:5,000), and cannot be used for site specific evealuation.

4.5 Physical Constraints to Development in Queenstown

The following section describes the major physical processes and conditions that have been identified by this study as affecting, or potentially affecting, development in Queenstown.

4.5.1 Stream Bank and Lake Shore Erosion

Stream bank and lake shore erosion can be defined as the progressive removal of material from the streambank or lake shore. The degree of erosion increases dramatically during heavy rainfall events, due to the increased stream flow rate and volume, and the increased sediment load (Figure 54).

Erosion of the shore of Lake Wakatipu is not much of a problem along areas of wide, gently inclined gravel beach, or rocky shores. However, the undercutting of silt, sand, and fill banks along the north shore of Frankton Arm was noted during field investigations following a series of heavy rainfall events during summer 1993-94, threatening the Frankton-Queenstown road in the vicinity of Marina Heights. Gabion baskets have been put in place to prevent further erosion. High lake levels coupled with strong winds (particularly from the south/southwest) result in wave action eroding weak, soft lake shore materials (lacustrine silts and sands).

There is a danger of small open streams running through developed areas eroding banks during high flow conditions, representing a threat to property. Poorly controlled stormwater discharged into roadside gutters/channels has caused erosion and undercutting of roads in the past (esp in fine grained sediments) (Figures 55 & 56)

Figure 54: An example of stream-bank erosion (from outside the study area). The Shotover River north of Arthurs Point is progressively eroding the sandy fine gravelly bank. Erosion is particularly accelerated during times of high river flow as was the case in February 1994.

Figure 55: Undercutting of S.H.6 south of the Kawarau Falls Dam following heavy rains February 1994.

Channel erosion of incised streams on steeper slopes. May undercut landslide toes and cause reactivation of slide mass, and consequent possible debris flow and deposition downstream.

4.5.2 Debris deposition

Channel aggradation resulting from deposition of alluvial debris during high intensity rainfall events is a physical process identified as posing constraints to urban development. Major mobilisation of stream bed, or of landslide debris should it be reactivated at the same time in the upper/mid catchment areas would pose a hazard to areas below, particularly on the outwash areas at the base of hill slopes with channel migration and debris deposition.

The main areas identified as being constrained by possible debris deposition are the stream channels and alluvial fan surfaces at the base of hills (Figure 57). These occur in Fernhill, Queenstown Gorge, along the Frankton-Queenstown road, and Kelvin Heights. Note that they are fed by in most cases deeply incised stream channels therefore any flow of debris will be constrained and rapid, until it spreads out onto fan or overtops the channel. Coarse, blocky schist debris layers have been identified within existing alluvial fans, representing deposition from debris flows in the past. Low-lying areas downstream of fans (eg Queenstown) could be affected by such events, should the stream channel change course (blockage of existing channel = flooding of surrounding/downstream areas) or if existing flood protection works fail.

Mitigation of the constraints posed by debris deposition and movement consists that watercourses and culverts have sufficient capacity to cope with "rock and soil [and vegetation]debris as well as large volumes of water". Culvert intakes and outfalls must be designed appropriately to prevent "intake blockage by debris and scouring in the

Figure 56: Erosion and debris deposition along Gorge Road following heavy rainfall in February 1994.

Figure 57: Braided channel migration and debris deposition on fan surface as a result of heavy rainfalls in February 1994, western footslope Remarkables. There was a significant amount of gravel debris deposited on S.H.6 and associated flooding.

region of the outfall". Concern has been voiced over culvert and stormwater design in the Fernhill and Marina Heights subdivision areas.

4.5.3 Slope Movements

As discussed in Section 3.4, foliation- and joint- controlled translational rock slides are common on the upper foliation dip slopes of the study area, notably above the Frankton-Queenstown road and on the south-facing slopes of the "Gondola Hill". Rock falls and topples characterise steep back-slopes such as above the Kelvin Heights Road controlled primarily by jointing and other subvertical defects. Minor slope failures in colluvium have been noted during this study,

The lack of detailed geotechnical data for the area precludes detailed analysis of landsliding conditions [landslide hazards]. Assessment of geological constraints imposed is based on the identification of existing slope movements through aerial photograph analysis and field observations, and interpreted on the basis of existing understanding of failures in schist terrain.

No evidence found during this study to suggest that recent movement has occurred on/within the slides in the study area with the exception of active scree slopes to the west of Queenstown, and the possible exception of the One Mile Creek landslide. The potential for mass movement in the area was assessed by the ULUC study to be very low.

The possibility of rock falls and/or topples originating from steep bluffs/slopes and blocky debris on landslide slopes is higher. In fact much of the foot slope and flat lying areas of Queenstown has the potential (however low) to be affected by rock falls/rolls/bounces from the moderately to steeply dipping slopes above.

The presently dormant state of identified landslides does not preclude further movement. Reactivation could be initiated by (Varnes 1978)

1. Removal of lateral and/or underlying support: by stream erosion or human excavation.
2. Surcharge: from weight of rain, hail, snow, or artificial fill and buildings etc.
3. Saturation of slide mass as the result of heavy rainfall, stream diversion, artificial ponding of water, etc
4. Seismic shaking

or by a combination of the above.

Small scale reactivation may include isolated slides/rolls/falls of schist blocks, small debris flows, with the potential to affect residential properties at the foot of the slope. Localised slumping, settlement in foundation soils may damage buildings. Small to large scale reactivation may lead to landslide damming of streams, and subsequent breach and debris flow - potentially very damaging to downslope property through deposition, erosion and flooding (Figure 58).

Ages of most recent movements not known, Existing slides are believed to be at least 10,000 years old. They are likely to have endured high intensity physical processes in that time, but there is no evidence for sudden, catastrophic failures in the study area. The likelihood of major reactivation in the future, given no significant change in present conditions, is considered to be small.

Figure 58: Showing the Marina Heights Slides perched above significant stream channels above a residential area.

4.5.4 Weak Foundation Materials

(A) Silt and Fine Sand Units

Silts and fine sands occur within two principal modes - as thick, massive or bedded units of lacustrine sediment, or as lenses within predominantly coarser deposits (fan-deltas, beach gravels). The silt content of the "silty till" also a (smaller) constraint.

The geotechnical properties of these fine grained sediments are highly dependant on their water content. Adequate site drainage, ensuring that any surface flows are diverted away from silty material, is considered to be crucial to avoid foundation instability problems. It is recommended that thorough geotechnical testing is carried out on a site specific basis for any prposed development on silt. Development may require site specific foundation design.

(B) Loose "Free-Running" Gravels

Loose, "free-running" (cohesionless) gravels in the study area are typically moderately well to well sorted, fines depleted, fine to medium gravels. Usually found/associated with beach deposits (abundant) and as layers/lenses within alluvial fan and fan-delta deposits. The problem is the low angle of repose for unsupported gravels (approximately 30°), which is likely to cause problems in excavations.

(C) Fault Zones Within Schist

Fault zone material may consist of extremely closely jointed to shattered schist, to a crushed schist clayey pug. As mentioned in a previous section, these zones can be less than one to tens of metres wide, are generally linear features.

The decrease in rock mass strength is of less significance to residential development than the groundwater seepages often associated with shattered/crushed zones. Jointing increases permeability, clayey crush zones form impermeable barrier to groundwater flow concentrating groundwater in perched zones.

4.5.5 Topography

The presently developed Queenstown area is bounded by moderately to steeply dipping slopes, which constrain the expansion of the town. The limit that topography places on development is not neccessarily a reflection of rock mass strength, but rather of the expense involved in construction (eg. extensive cut and fill required). It is to be noted however, that extensive excavations arelikely to increase the probability of slope failure.

4.5.6 Others

(A) Inundation by Flooding

A Floodplain Management Report has been prepared for the Queenstown-Lakes District Council by the Otago Regional Council, a draft (May 1993) of which was made available to the author (was to be updated February 1994). This document discusses in detail the causes and extents of flooding (to date) and evaluates mitigation options with the aim of [preparing] a suitable/optimal floodplain management plan.

Several high intensity rainfall events since settlement in the Queenstown Bay have resulted in damaging floods in the town centre from Bush and Horne Creeks (Otago Regional Council 1993). A recently completed flood protection scheme involving two detention dams was designed to pass the 1% flood, restricting design flows between the sportsground and the lake to $15.5 m^3 s^{-1}$ (Otago Regional Council 1993).

The principal inflows of Lake Wakatipu are Rees and Dart Rivers, plus the Von, Greenstone and Caples Rivers which all flow into the western arm of the lake, and the Lochy River in the eastern arm. Also when the level in the Shotover River is high it has the potential to back up the Kawarau River to such a level that outfall from Lake Wakatipu is obstructed, adding to flood levels of the lake.

Highest recorded lake level was 312.6m in September 1878. Within the last twenty years, the lake has reached a maximum level of 311.69m asl (January 1983), and has passed 311.0m on seven different occasions, the most recently when it reached 311.67 after rising steadily for 2-3 weeks (Works Power Engineering, unpubl data, 1994) (Figure 59). The Otago Catchment Board (1993) have calculated the following probabilities of lake levels being reached or exceeded in any given year:

Probability	Metres a.s.l
1%	311.98
2%	311.75
5%	311.66
10%	311.26
20%	311.06
50%	310.70

A "lake flood hazard zone" has been established around Queenstown Bay, below the 312.0m (asl) contour line, within which development is controlled with respect to possible flood events (Otago Regional Council 1993). It should be noted here that wind generated waves will exacerbate the flood situation. The Combined District Scheme (1985) required that buildings within the Commercial 1 zone be able to cope with water

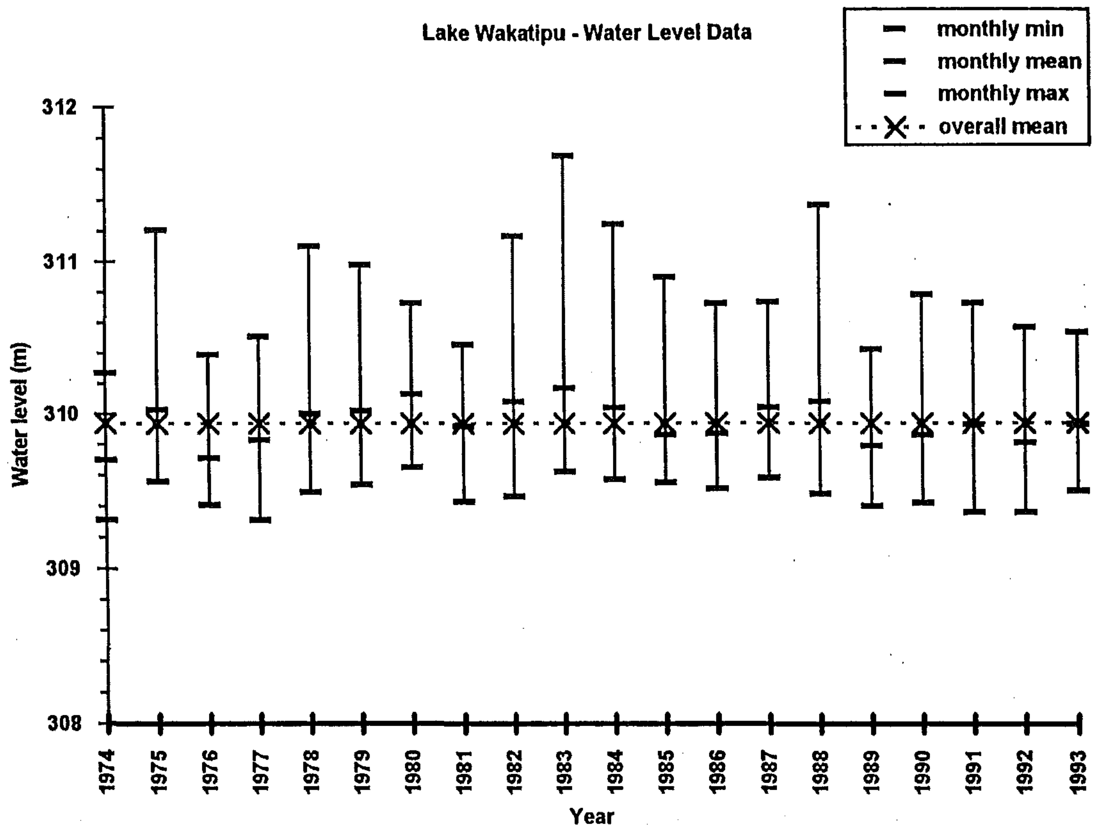


Figure 59: Maximum, minimum, and mean yearly lake levels, Lake Wakatipu.
(data from Works Consultancy Services, Wellington)

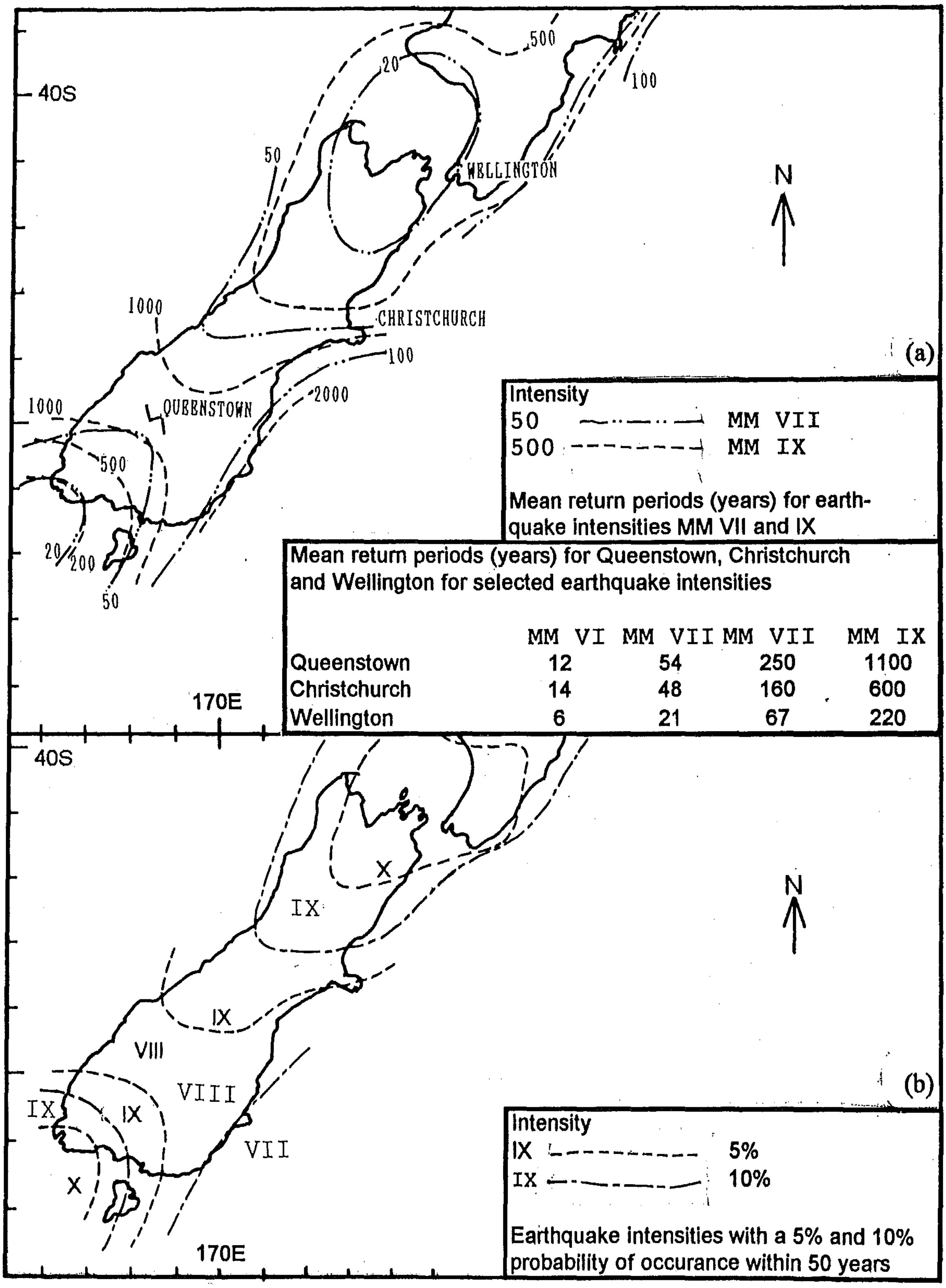
levels of 312.0m or greater.

(B) Seismicity

Smith and Berryman (1983) have estimated earthquake effects and likely return periods for the whole of New Zealand on a regional basis (Figure 60). These estimations do not take into account local variations in ground motions caused by differences in geology, structure, soils etc., and therefore are intended as a guide only. Likely mean return periods for earthquakes of given intensities affecting Queenstown are presented in Figure 60(a). Although the Moonlight Fault Zone and Nevis-Cardrona Fault System are classified as active (Hancox et al 1986), the Wakatipu region is in one of the most seismically quiet zones of New Zealand (Smith and Berryman 1983). The conceivable Maximum Credible Earthquake (MCE) with a probability of occurrence within 150 years, for the Moonlight, Cardrona and Alpine faults are Ms 7.5, 7.4 and 8,5 respectively (Hancox et al 1985). Is likely that movement on any of the main faults could be taken up on subsidiary faults in the area (Hancox et al 1985).

The three principal earthquake induced processes are: (1) surface ruptures (along fault traces); (2) ground shaking; and (3) ground failure (for eg. subsidence, landsliding, differential settlement) (Johnson and De Graff 1988). Ground shaking intensity from one earthquake will be spatially variable, depends on the nature of the foundation materials. For example, earthquake intensity is greater for thick, saturated soils than it is for competent rock (Johnson and De Graff 1988).

Liquefaction of fine grained, saturated soils can occur during seismic ground shaking, whereby the pore pressure increases and the soil is reduced to a liquid state (usually suddenly). the soil suffers an often sudden loss of strength (Ishihara 1993). This may lead to differential settlement of the soils, and flow of soil on gentle slopes. Cohesionless soils with non-plastic fines content of 5% are most susceptible to liquifaction in the



	MM VI	MM VII	MM VII	MM IX
Queenstown	12	54	250	1100
Christchurch	14	48	160	600
Wellington	6	21	67	220

Figure 60: Earthquake intensities and return periods for the South Island (from Smith and Berryman 1983).

(a) Mean return periods for earthquake intensities MM VII and IX, and calculated mean return periods for Queenstown in comparison to Christchurch and Wellington.

(b) Earthquake intensities with 5% and 10% probability of occurring within 50 years.

(NB. explanation of Modified Mercalli scale (MM) given in Appendix E) saturated state (Ishihara 1993). Liquefaction of soils in the Queenstown urban area is unlikely, however, specific testing should be done on "at risk" soils.

Severe shaking also results in landslides of unstabnle material, and rockfalls. There is a possibility that identified areas of existing landslides could be reactivated by ground shaking, especially when coupled with high ground water contents.

Several small faults (crush zones) have been identified in the Queenstown urban study area (refer Section 3.3), but with the possible exception of the "Queenstown Fault" and Newman fault (?) and Watts ft, these features have not disturbed Quaternary sediments although that does not preclude future movement.

There is a small possibility of earthquake-induced landsliding, particularly coupled with period of high groundwater content (eg following/during high intensity rainfall). The majority of the large existing slides have most likely been subjected to strong ground shaking within their lifetimes, with no evidence for rapid, catastrophic slope movement having occurred. Small localised reactivations of debris, rockfalls/topples, and localised failures in colluvium, poorly engineered fill, etc are more likely. Such failures will be dependant in part on groundwater conditions.

4.6 Synthesis

- Engineering geology has a significant application to land use planning. It provides the means to assess the physical characteristics of an area so that the potential effects of development on the environment, and vica versa, can be evaluated.

- The terrain evaluation approach to land use planning is suitable if it incorporates the identification of physical constraints, and is supported by geotechnical data. The

ULUC survey conducted in Queenstown in 1988 had a major weakness in that it lacked geotechnical data and showed a poor understanding of thee concepts in constraint zoning.

- Five major constraints to residential development have been identified in the Queenstown urban area. They are erosion of stream and lake banks, debris deposition, slope movement, weak foundation materials, and topography. Flooding and seismicity also pose significant limitations to development, however flooding has been expressly dealt with by the Floodplain Management Report, and seismicity is not within the scope of this report.

CHAPTER FIVE: PROPOSED ZONING APPROACH: LIMITATIONS TO DEVELOPMENT IN THE QUEENSTOWN URBAN AREA

5.1 Introduction

The main objective of this thesis is to produce a map that indicates the types and distributions of the principle physical constraints affecting (or potentially affecting) residential development in the Queenstown urban area, and shows the degree to which development is limited by the constraints. This chapter describes the Development Suitability Map (1:10,000) that was formulated with this objective in mind.

The zonation approach proposed for the Queenstown urban area is based on the engineering geology methodology discussed in Section 4.3, and follows the approach utilised by Horrey (1989). The difference being that this study has chosen to zone the land according to the limitations that existing and potential physical constraint impose on residential development.

5.2 The Development Suitability Map

A Development Suitability Map (Figure 8, map pocket) covering the Queenstown Urban Area has been prepared at a scale of 1:10,000. Physical constraints data was obtained directly from the engineering geological database. The outlines of features such as landslides, recent alluvial fans, stream channels and significant geologic units were transferred directly from the engineering geology map to the Development Suitability map using AuoCad, and were supplemented by existing literature, previous assessments of physical constraints and field data concerning presently and recently active processes (eg. erosion and debris deposition subsequent to heavy rainfall).

The degrees of limitation for each constraint were assessed on the basis of terrain classification using estimations of the age of the most recent activity in the cases of physical processes, and an evaluation of engineering properties in the case of physical conditions.

The Development Suitability Map uses a very simple zonation scheme to show what physical constraint is affecting any given area, and what degree of limitation it imposes on residential development. A four-fold zonation scheme is used (low-moderate-high-extreme) to describe the degree of limitations that the physical constraints (debris deposition, stream and lake bank erosion, slope movement, weak foundation material, and topography) impose on residential development (Table 12). Letters are used on the map to define each zone. For example, "Mt" denotes an area with a moderate limitation imposed on it by topography. Colours are used to group areas of similar degrees of limitation together and thus highlight suitable/unsuitable areas.

This simple zonation scheme works for the Queenstown area because most of the zones are defined by only one constraint, or by one degree of limitation. This method would not be applicable where two different constraints were affecting the same area with different degrees of limitation.

The outcome that this zonation scheme is geared towards is the evaluation of the suitability of the land for residential development and the amount of further site investigation that is likely to be needed. The Development Suitability Map is intended for land use planners and administrators within the Queenstown Lakes District Council and elsewhere to quickly and easily identify those areas that may be less than suitable for

DEGREE OF LIMITATION	TYPE OF CONSTRAINT				
	Debris Deposition (d)	Stream and Lake Bank Erosion (e)	Slope Movement (s)	Weak Foundation Material (f)	Topography (t)
EXTREME (E) Development most improbable	Areas of active debris deposition - stream channels, active fans, and deltas	Areas of active erosion - stream channels, lake shore (non rock)	Presently active slope movement - block and debris slides, active scree slopes	//	Slopes steeper than 65 deg. in rock and soils
HIGH (H) Requires full site specific geotechnical investigation and engineering foundation design. Significant limitations.	Areas where debris deposition, siltation, and channel migration have occurred in the recent past (1 yr) as a result of high intensity rainfall events	Areas where erosion has occurred in the recent past (1yr) as a result of high intensity rainfall events	Presently inactive landslides. Includes degraded debris mass, head/lateral scarp and toe zones, and any areas of likely retrogression	//	Slopes steeper than 45 deg. in rock and soils
MODERATE (M) Requires engineering geological investigation, including geotecnical testing as required. May require site specific design. Generally suitable for development	Areas where debris deposition, siltation, and channel migration may occur as a result of an extreme rainfall event, possibly coupled with landslide damming and release	Areas where erosion may occur as a result of an extreme rainfall event	Areas of potential instability due to foliation attitude in relation to slope, presence of weak fissile schist, etc	Areas where foundation materials include silts, loose gravels, crush and fault zones within schist. Also includes areas of swamp	Slopes steeper than 30 deg in rock and soils
LOW (L) No further investigations required. Follow normal engineering practices Suitable for development.	Suitable for residential development given normal engineering prudence, especially with regards to adequate drainage provision (channels,culverts)			Note: till, fan and fan-delta deposits may contain significant silt lenses	

Table 12: Key to the Development Suitability Map

development. It does not take into account any change in conditions that may result from future development.

As the Development Suitability Map is derived from the engineering geology map, the same cautions apply concerning the amount of inference used to determine the distribution of material and geological features, and the resulting degree of interpretation. However, the map is felt to give a good representation of active and potentially active processes and conditions affecting development in the Queenstown Urban Area.

The map is not intended as a substitute for proper engineering site investigations. Its primary use is as an aid to land use planning, at a scale of 1:10,000. Development suitability is identified on an engineering geological basis only. Other factors such as user compatibility, and servicing constraints (provisions for water supply and waste disposal for example) are not taken into consideration.

5.3 Synthesis

- A Development Suitability Map has been compiled at a scale of 1:10,000 which zones land in the Queenstown urban area according to the type of physical constraint present and the degree of limitation imposed on residential development, thus identifying areas that are more suitable for future development than others based on an engineering geological assessment.

- The Development Suitability Map represents the primary objective of this study. That is, the compilation of relevant engineering geological data into a zonation map that can be used by land use planners (and others) as an input to land use planning and management decisions.

CHAPTER SIX: SUMMARY

- There is a high demand for residential properties in the Wakatipu region, and in the Queenstown urban area in particular. Hence there is pressure on local authorities to provide for expansion yet without compromising the integrity of the settlement, or exposing property to potentially damaging physical processes or conditions, and without adversely affecting the environment.

- This study was undertaken to provide information on expected foundation materials and conditions in the Wakatipu Basin, but more importantly in the Queenstown urban area, and to determine the nature and extent of geological processes and conditions with the potential to affect residential development.

- Engineering geological mapping was undertaken at a scale of 1:25,000 in the Wakatipu Basin, and at a scale of 1:10,000 in the Queenstown urban area. From the 1:10,000 engineering geology map of the urban area a Development Suitability map has been compiled. This map subdivides the area according to the type of physical constraint present, and the degree of limitation to development that the constraint imposes.

- The basement rocks of the Wakatipu Basin consist of grey- and greenschists of the Otago Schist. Glaciation during the Quaternary is responsible for much of the erosion of the bedrock to its present form, and for the deposition of glacigenic deposits. Preservation of the glacigenic sediments is poor, and repeated advance and retreat cycles have resulted in a complex stratigraphic situation. Lake Wakatipu, following ice retreat (ca. 14,000ya) was much enlarged from its present size and elevation as evidenced by numerous high level beach terraces, the extensive deposits of lacustrine silts, and the high level fans and truncated fan-deltas.

- The schist terrain has been subjected to extensive slope modifications. The dominant types of slope failures in the Basin are translational planar and wedge rock slides controlled primarily by foliation and foliation shear zones, and secondarily by other rock mass defects (joints, crush zones), which occur on slopes that are subparallel to the strike of foliation but dipping more steeply. Rock falls and topples are common on steep, jointed slopes.

- This study has produced a zonation map at a scale of 1:10,000 that is suitable as a guide to likely site conditions. It has drawn on limited geotechnical data from a wide range of sources, and is therefore incomplete with respect to material characterisation. It is recommended that an extensive collation of existing geotechnical data (presently held by various engineers, geologists, and others) on Queenstown materials be conducted to form a central database accessible to all interested parties, possibly combined with a directed program for continued geotechnical testing.

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APPENDICES

A: List of Aerial Photographs Used

B: Engineering Geological Descriptions of Rock and Soil

C: List of Civil Engineering Consultants Reports Made Available to this Study

D: Grainsize Curves, and engineering geological descriptions for those samples without photographs

E: Description of the Modified Mercalli Scale

APPENDIX A

LIST OF AERIAL PHOTOGRAPHS USED

LIST OF AERIAL PHOTOGRAPHS USED

RUN	NUMBERS
2291	68, 69, 70
2292	71, 72, 73, 74, 80, 81, 82, 83
2293	33, 34, 35, 36, 37
3972	34, 35, 36, 37
S133	1/B, 1/A
SN 3857C*	12, 13, 14, 15, 16, 17
SN 3857D*	9, 19, 11, 12, 13, 14, 15, 16, 17
SN 5211A*	1, 2
SN 8180G*	1, 2, 3, 4
SN 8180H*	1, 2

* coverage of Queenstown Urban Area

APPENDIX B

ENGINEERING GEOLOGICAL DESCRIPTIONS FOR ROCK AND SOIL

WEATHERING

TERM		ROCK DESCRIPTION
Residual Soil	RW	discolouration and complete transformation to soil, original fabric destroyed
Completely Weathered	CW	discolouration and transformation to soil, original fabric largely preserved
Highly Weathered	HW	material pervasively altered with discolouration and loss of strength fabric preserved, lithorelicts
Moderately Weathered	MW	penetrative discolouration and alteration of rock material, with some loss of strength
Slightly Weathered	SW	slight discolouration of rock fabric, no loss of material strength
Unweathered	UW	no discolouration or loss of strength, or any other effects due to weathering

STRENGTH

TERM	POINT LOAD STRENGTH INDEX Is(50)	FIELD ESTIMATION OF STRENGTH
Extremely Strong	> 10	can only be chipped with geological hammer
Very Strong	3 to 10	several hard blows required to break hand speciman
Strong	1 to 3	few firm blows of hammer required to break speciman
Moderately Strong	0.3 to 1	breaks readily with one blow of hammer
Moderately Weak	0.1 to 0.3	broken by hand only with difficulty; small thin pieces broken by finger pressure
Weak	0.05 to 0.1	broken by hand, pieces 25mm or more broken by finger pressure
Very Weak	< 0.05	crushed or remoulded by hand (grades into soil material)

FABRIC

Finely layered	< 25 mm thick
Coarsely layered	> 25 mm thick
Massive	
Other	specify

DEFECT SPACING

TERM	SPACING (mm)
Extremely wide	> 2000
Very wide	500 to 2000
Wide	200 to 500
Moderate	100 to 200
Close	25 to 100
Very close	5 to 25
Extremely close	< 5

ROCK MASS DEFECTS

DEFECT TYPE		DESCRIPTION
Layering	Bedding Foliation Cleavage	1. Arrangement in layers of mineral grains or crystals of similar size or composition 2. Arrangement of elongate or platy minerals near parallel to one another and/or the layers
Fractures and Fracture zones	Joint / Fault	Single fracture across which rock has little tensile strength; planar, curved, or irregular; open, closed, or incipient; surface rough, smooth or slickensided.
	Sheared Zone	Zone of multiple closely spaced (<100mm) fracture planes, with roughly parallel planar boundaries, blocks of intact material within zone typically lenticular or wedge shaped; fractures closed, open, weakly cemented or soil coated.
Weak Seams or Zones	Crushed	Zone with roughly parallel planar boundaries- 1. Composed of disoriented, usually angular, fragments of variable size in a soil matrix 2. Some weathering of fragments possible, with soils either cohesive or noncohesive. 3. Lowest shear strength parallel to zone boundaries, which are commonly slickensided.
	Decomposed	Zone of any shape, but commonly with roughly parallel planar boundaries. Within zone rock MW to CW; margins grade into fresh rock.
	Infilled	Zone of any shape, but commonly with roughly parallel planar boundaries. Composed of soil materials which may show layering roughly parallel to zone boundaries; rock fabric not present in infill zone.

COLOUR

	pinkish	pink
	reddish	red
	yellowish	yellow
light	brownish	brown
	orangey	orange
medium	olive	olive
	greenish	green
dark	bluish	blue
	whitish	white
	greyish	grey
		black

Colour; Weathering; Strength; Fabric; Rock Name.

Rock Mass Defects.

Engineering Geological Field Description for Rock Material

COLOUR

	pinkish	pink
	reddish	red
	yellowish	yellow
light	brownish	brown
	orangey	orange
medium	olive	olive
	greenish	green
dark	bluish	blue
	whitish	white
	greyish	grey
		black

WEATHERING

TERM		SOIL DESCRIPTION
Completely Weathered	CW	completely discoloured and altered, no trace of original fabric
Highly Weathered	HW	mostly altered and weakened little trace of original fabric
Moderately Weathered	MW	large discoloured portions of original soil separated by more altered material, significantly weakened
Slightly Weathered	SW	minor discolouration of some parts of the original soil, no loss of strength
Unweathered	UW	original soil with no discolouration, loss of strength or other effects due to weathering

NOTE: In coarse grained soils record weathering grade of dominant fraction, and qualify weathering grade of subordinate and/or minor fractions if appropriate.

WATER CONTENT

TERM	FIELD CRITERIA
Dry	looks and feels dry; fine grained soils usually hard, powdery, or friable; coarse grained soils may run freely through hands
Moist	soil feels cool and may be darkened in colour; particles tend to adhere in coarse grained materials, fine grained soils may be softened
Wet	soils feel cold and are darkened in colour; free water forms on hands when sample is disturbed
Saturated	restricted to wet soils below the water table or the static water level in excavations or drill holes

STRENGTH

TERM	FIELD CRITERIA
Loose	can be removed from exposure in disaggregated form by hand
Compact	only removed from exposure by implement, material readily disaggregated by physical means
Cemented	only removed from exposure by implement, material does not disaggregate (may require description as rock material)
Hard	may be removed from exposure with difficulty by implement or hand, softened on immersion in water and may be remoulded
Stiff	indented by thumb pressure, but not moulded by fingers, softened on immersion in water and may be remoulded
Firm	moulded or indented only by strong finger pressure, easily moulded after immersion in water
Soft	easily indented or moulded by finger pressure
Very soft	exudes between fingers when squeezed
Spongy	readily compressed by finger pressure, but cannot be remoulded

FABRIC

Finely layered	< 25 mm thick
Coarsely layered	> 25 mm thick
Massive	
Other	specify

PARTICLE SIZE

Cobble		> 60 mm
Gravel	coarse	20 - 60 mm
	medium	6 - 20 mm
	fine	2 - 6 mm
Sand	coarse	0.6 - 2 mm
	medium	0.2 - 0.6 mm
	fine	0.06 - 0.2 mm
Silt		0.002 - 0.06 mm
Clay		< 0.002 mm

Subordinate fraction (20-50%)

Minor fraction: with - trace (<5%)
minor (5-10%)
some (10-20%)

Colour; Weathering; Water Content; Strength; Fabric; Grain Size.

Clast Description Other Distinguishing Features

Engineering Geological Field Description for Soil Material

APPENDIX C

LIST OF CIVIL ENGINEERING REPORTS MADE AVAILABLE TO THIS STUDY

ENGINEERING REPORTS

Duffill, Watts and King

Commonage Subdivision (March 1989). Job no. 13663, file 4162/27
Malaghan Street Development (August 1985).
Lake Esplanade Walkover (December 1992). file 4166/33/2

Royds Consulting Ltd

92169 Steamer Wharf (April 1993)
7306 Mobil Site, Frankton (April 1991)
17561 Proposed house site, Frankton Beach (December 1992)
7567 Sunshine Bay Stage 8, Fernhill Rd (August 1985)
17731 Argyle Properties Building, Industrial Lane (August 1993)
17861 Earnslaw Terrace (January 1994)
17859 Country Lodge, Queenstown
7247 Lot 2, Sec. 6, Block XLVI (September 1990)
7764 Lot 22, Aspen Grove Subdivision, Fernhill (September 1993)
7269 Ullrich House, Manchester Place, Queenstown (November 1990)
7272 Old National Bank Building, Rees St (April 1991)
7602 Lot 20, Golden Terrace (February 1993)
7743 Wye Place, Sunshine Bay (September 1993)
7414 Greenstone Place
7685 York St (November 1993)
17744 Johnstone House, Kelvin Heights (August 1993)
7395 Lot 50, Edinburgh Drive (January 1992)
7234 Holdsworth Subdivision (July 1990)
7309 Guthrie Building
7542 Queenstown LPG Centre, Gorge Road (November 1992)

APPENDIX D

GRAINSIZE DISTRIBUTION CURVES

SAMPLE: G **LOCATION:** Kelvin Heights Golf Course

DESCRIPTION:
Light brownish grey; SW; dry; firm; massive; moderately well sorted; micaceous; silty fine to medium SAND.

INTERPRETATION:
Lacustrine sand

GRAIN SIZE DISTRIBUTION:
% Gravel: .0 **% Sand:** 63.0 **% Mud:** 37.0

SAMPLE: I **LOCATION:** Loop Road, Kawarau Falls.

DESCRIPTION:
light orangey grey; SW; dry; loose; massive; poorly sorted; fine to coarse sandy fine to coarse GRAVEL, with occasional cobble, trace silt. Clasts predominantly subangular to subrounded schist and quartz, minor rounded greywacke, slightly imbricated.

INTERPRETATION:
Beach gravels.

GRAIN SIZE DISTRIBUTION:
% Gravel: 59.7 **% Sand:** 37.7 **% Mud:** 2.6

SAMPLE: O **LOCATION:** Queenstown Hill walking track

DESCRIPTION:
Light brownish grey; SW; moist; extremely compact; massive; poorly sorted; medium gravelly fine SAND, with some silt, occasional cobbles. Clasts predominantly rounded greywacke, abundant subangular to subrounded schist.

INTERPRETATION:
Silty till

GRAIN SIZE DISTRIBUTION:
% Gravel: 31.9 **% Sand:** 49.3 **% Mud:** 18.8

SAMPLE: Q **LOCATION:** The Commonage

DESCRIPTION:
Light brownish grey; SW; moist; firm; massive; well sorted; silty fine SAND, with minor fine gravel. Clasts subangular schist.

INTERPRETATION:
Sand layer within till

GRAIN SIZE DISTRIBUTION:
% Gravel: 5.9 **% Sand:** 47.9 **% Mud:** 46.2

SAMPLE: R **LOCATION:** Andrews Road, Frankton Arm.

DESCRIPTION:
Light yellowish brown; SW; moist; firm; massive; well sorted; fine to medium SAND, with trace silt and gravel. Clasts subangular schist.

INTERPRETATION:
Lacustrine sand

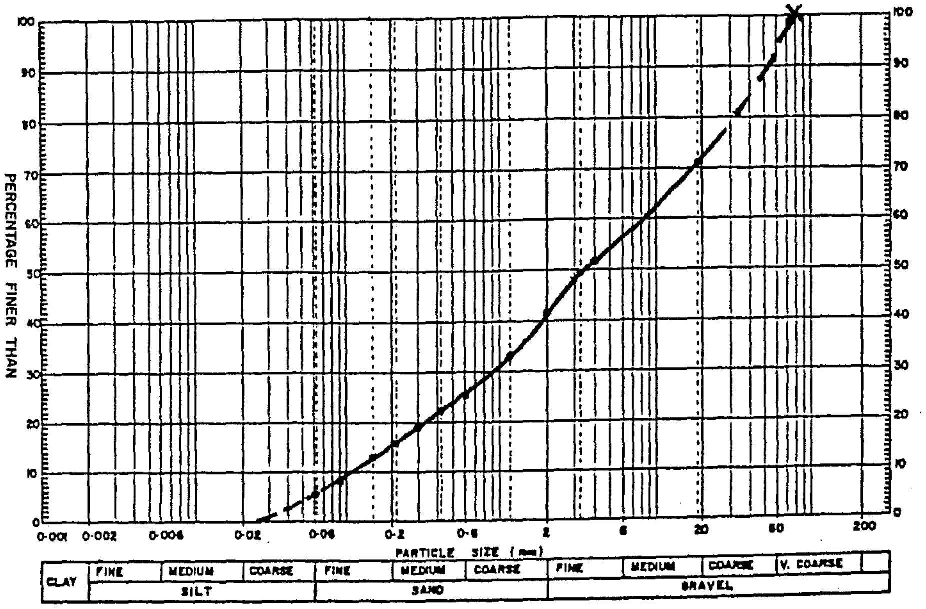
GRAIN SIZE DISTRIBUTION:
% Gravel: 0.3 **% Sand:** 96.5 **% Mud:** 3.2

SAMPLE: S **LOCATION:** State Highway 6, Frankton.

DESCRIPTION:
Medium orangey brown; SW-MW; dry; slightly layered, gently inclined; poorly sorted; fine gravelly medium to coarse SAND, with trace silt. Clasts predominantly subangular to subrounded schist, rare rounded greywacke.

INTERPRETATION:
Beach gravel

GRAIN SIZE DISTRIBUTION:
% Gravel: 44.1 **% Sand:** 54.8 **% Mud:** 1.1



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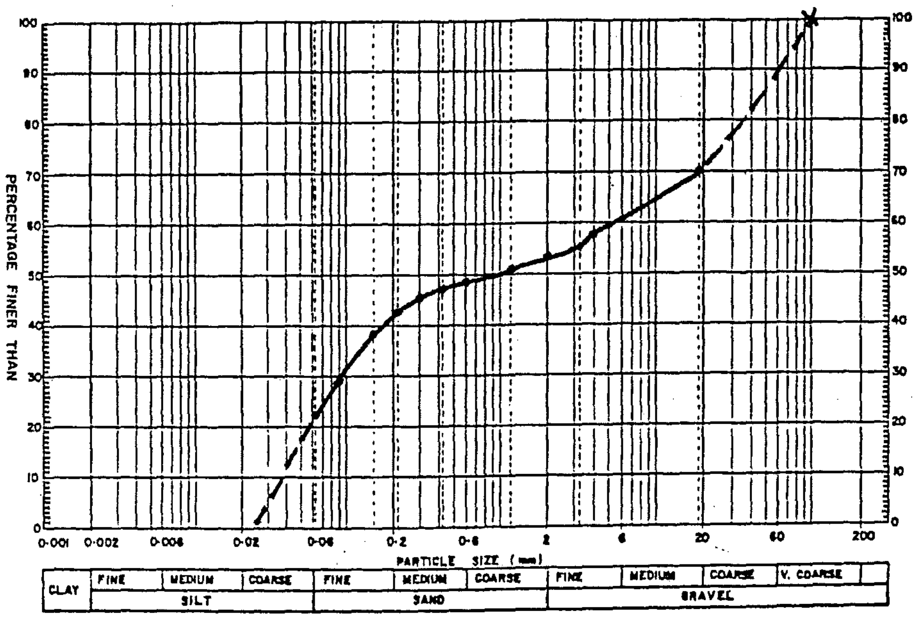

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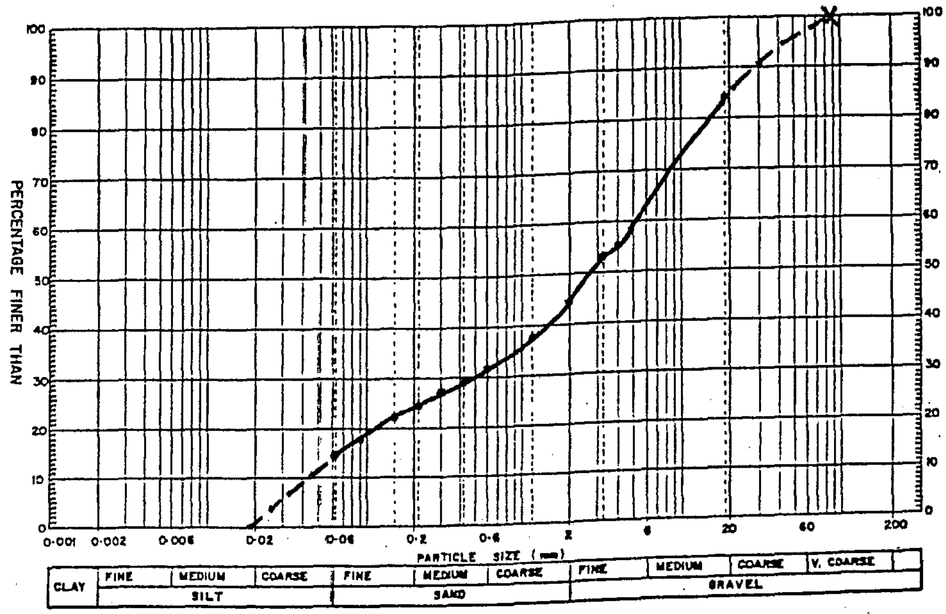

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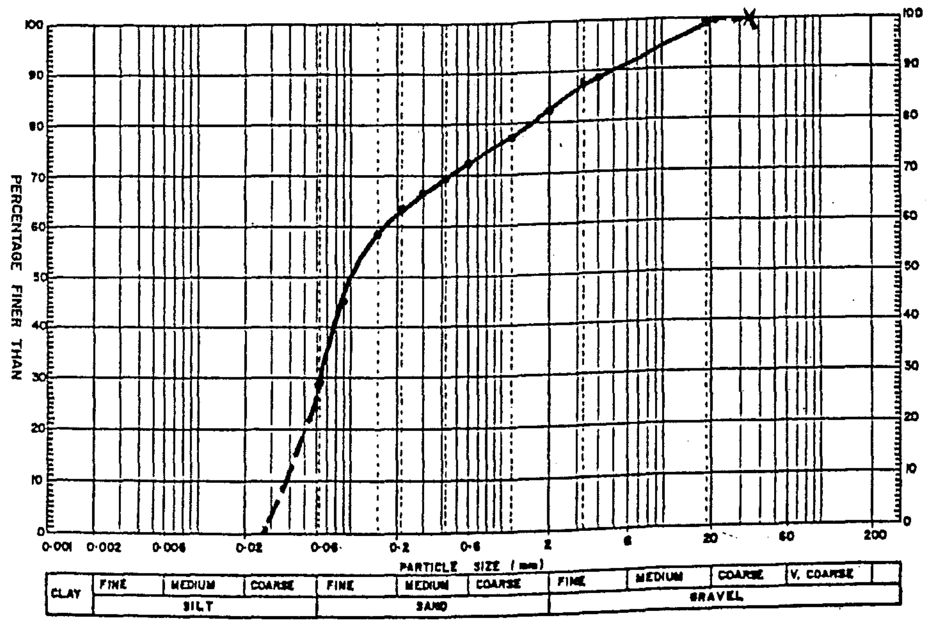
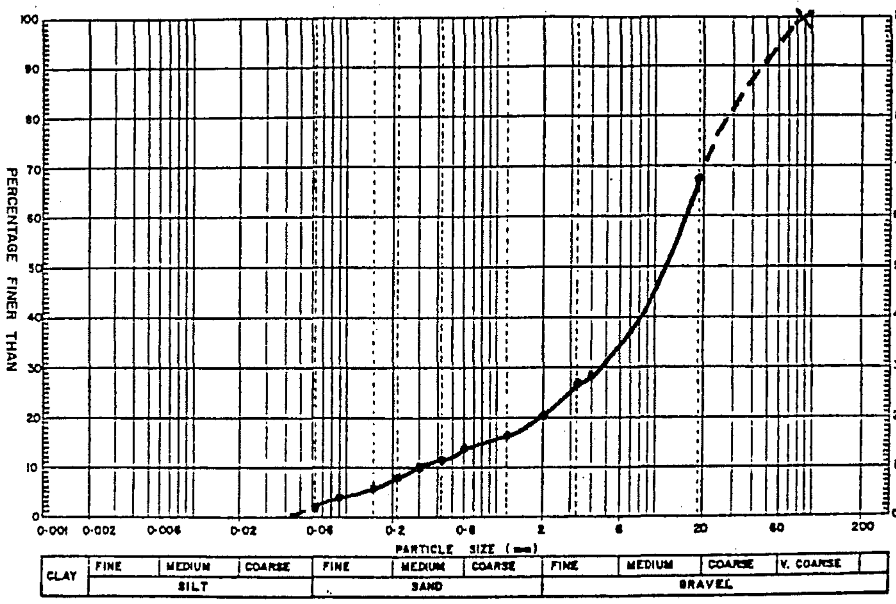


SAMPLE: C



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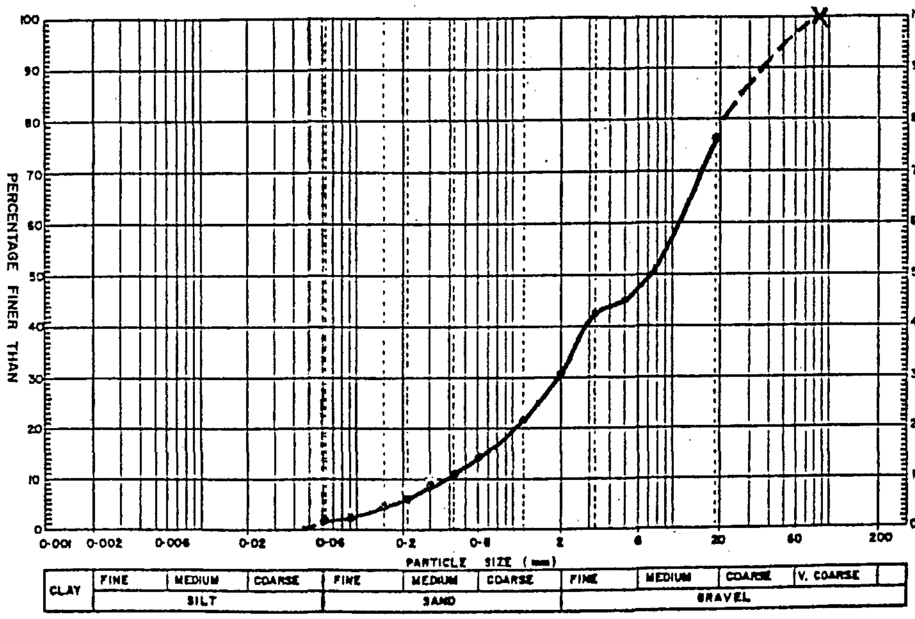

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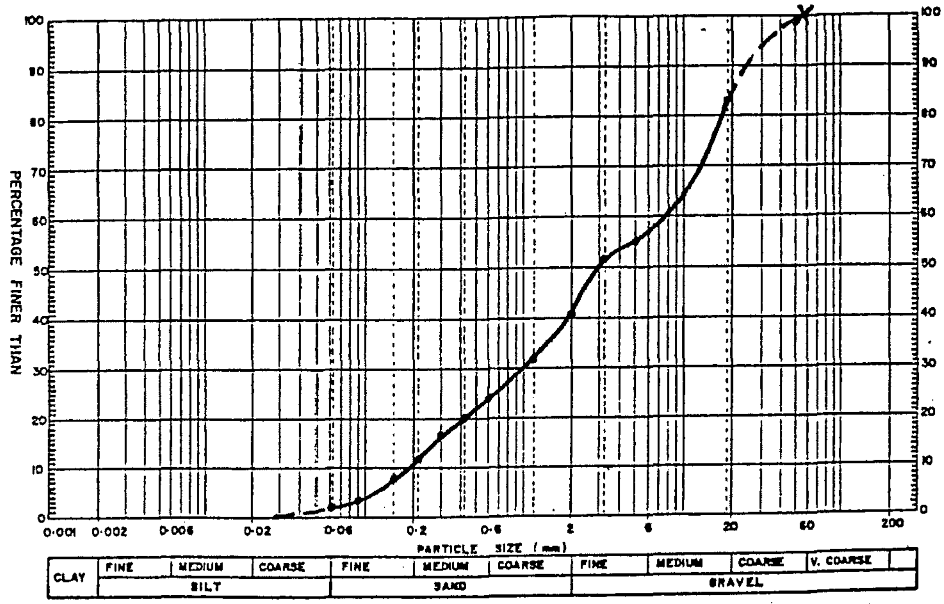
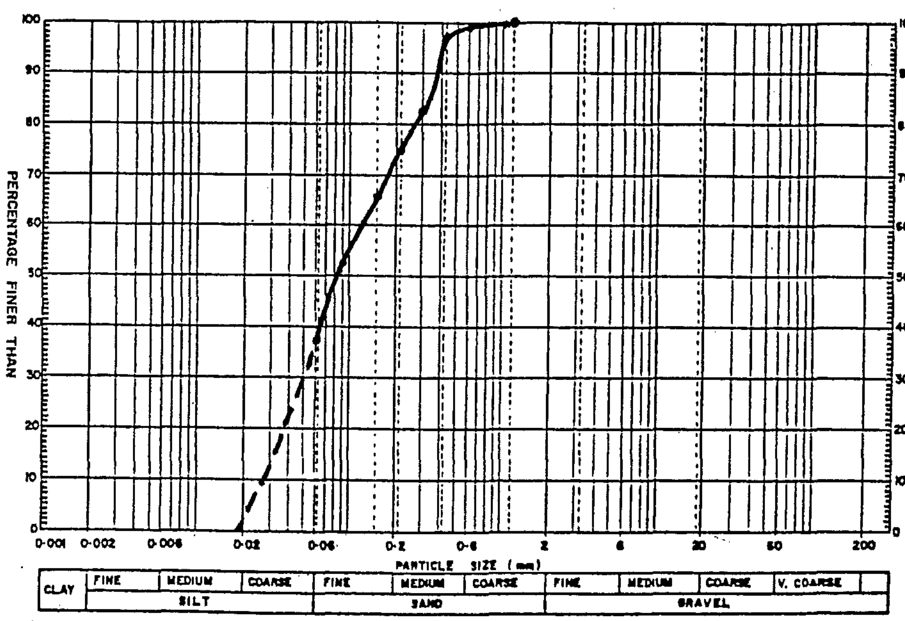
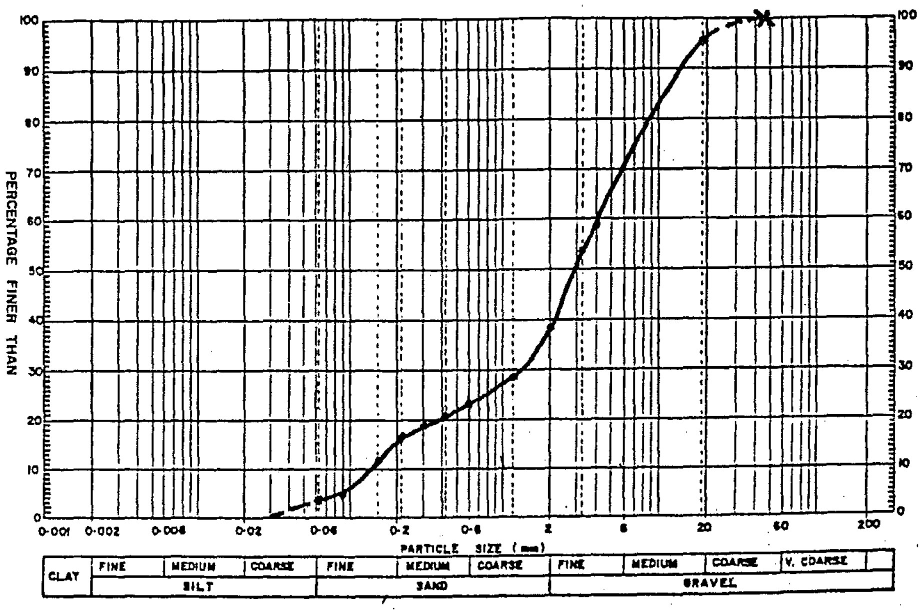


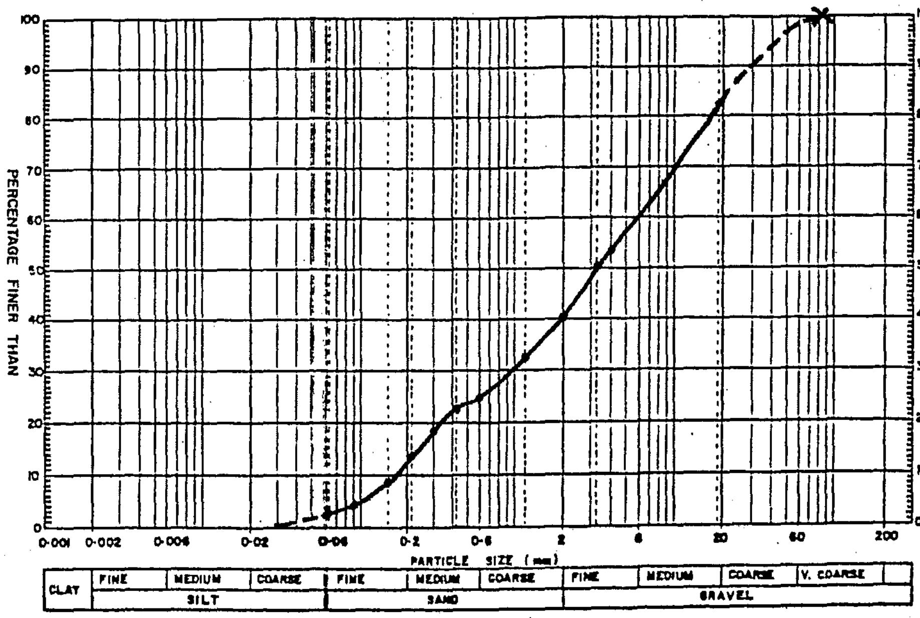
SAMPLE: F



SAMPLE: G



SAMPLE: H



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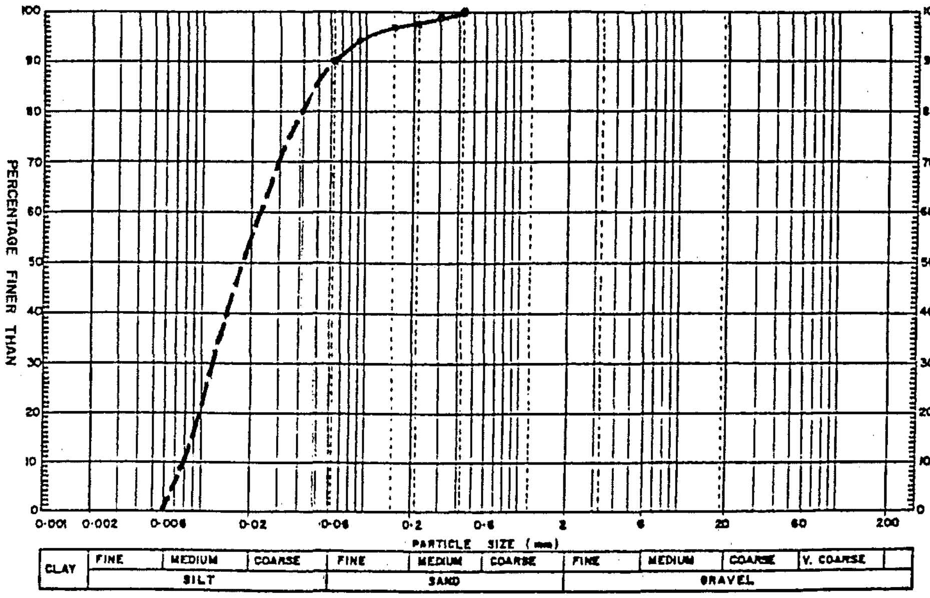

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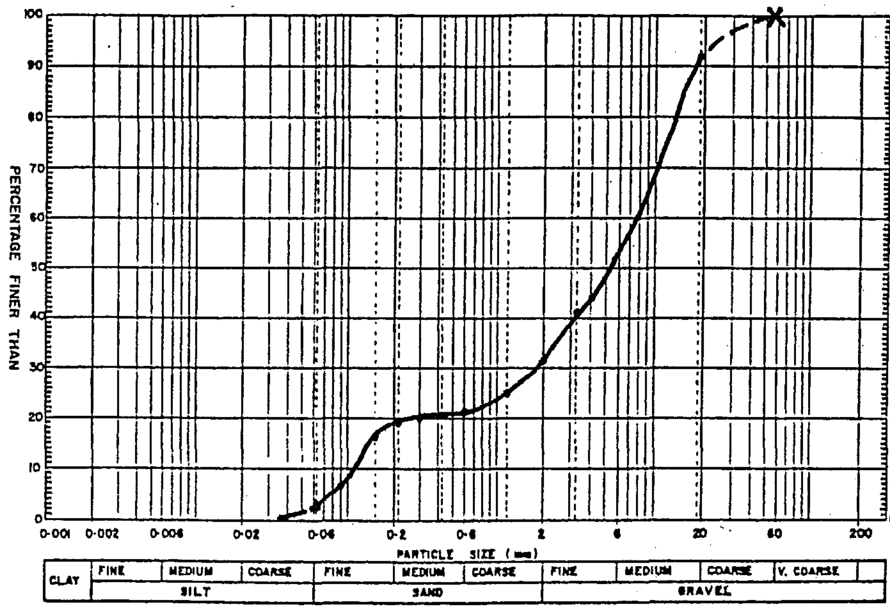
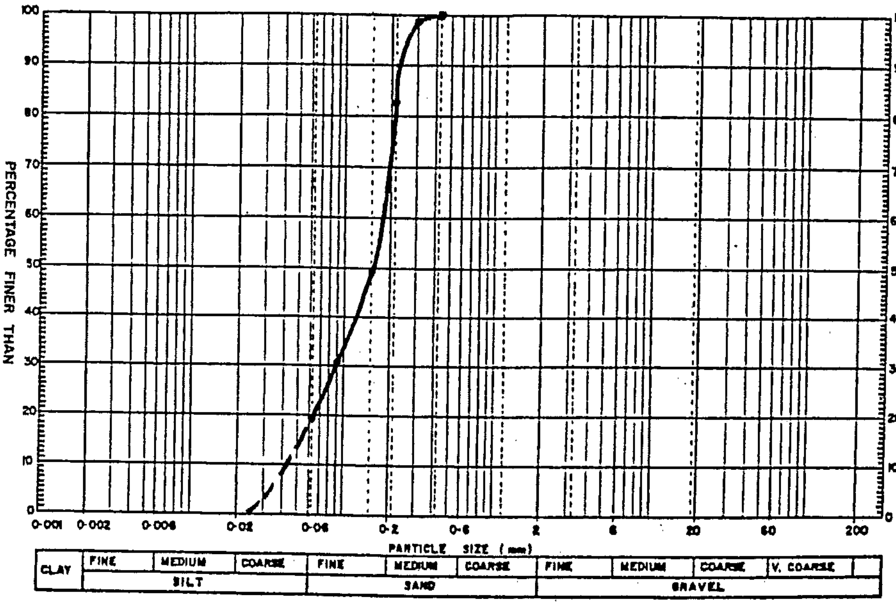
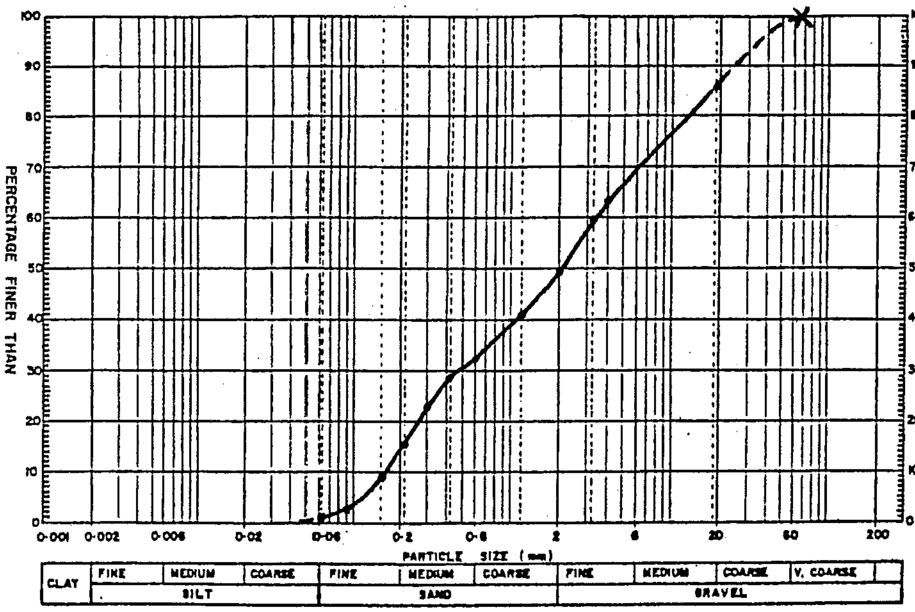


SAMPLE: K1



SAMPLE: K2



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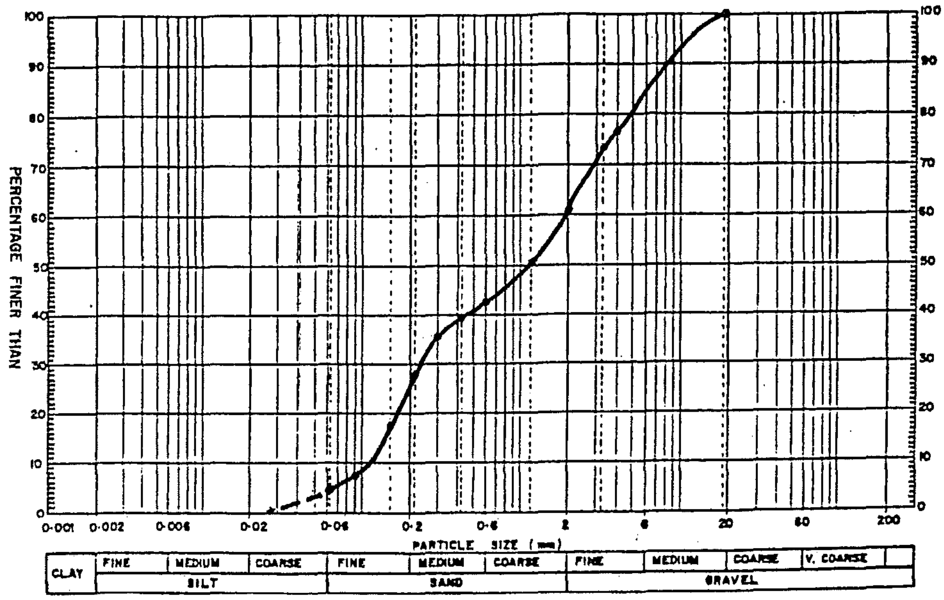

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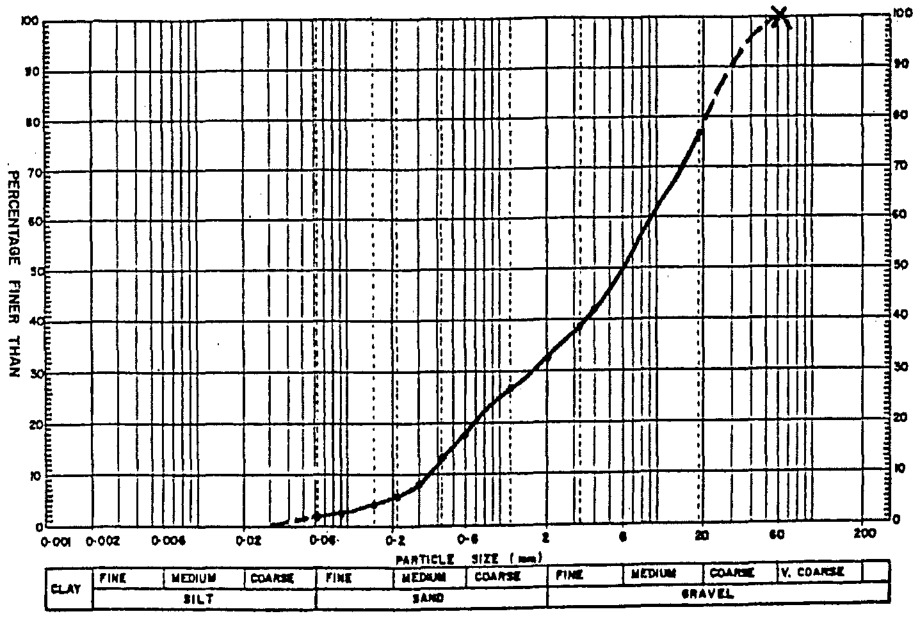

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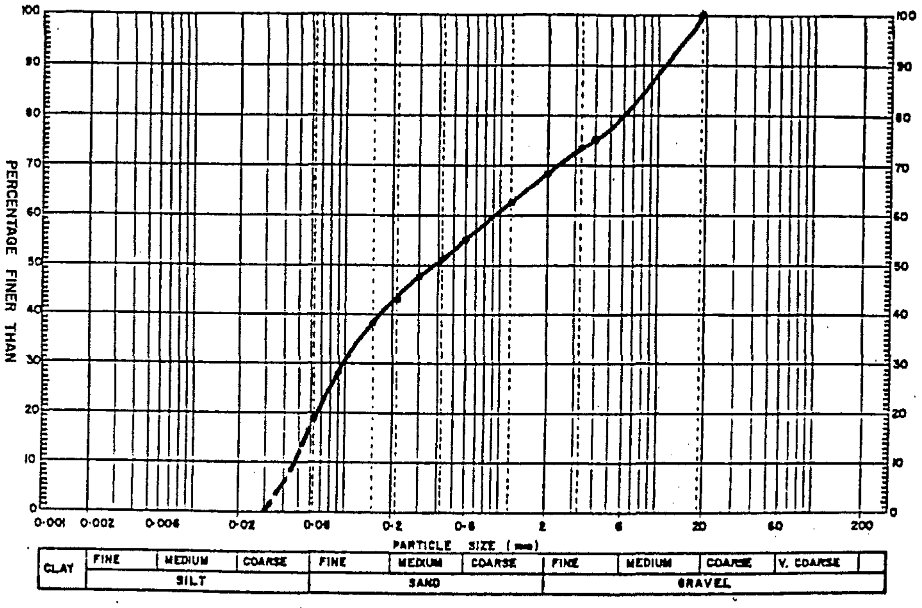
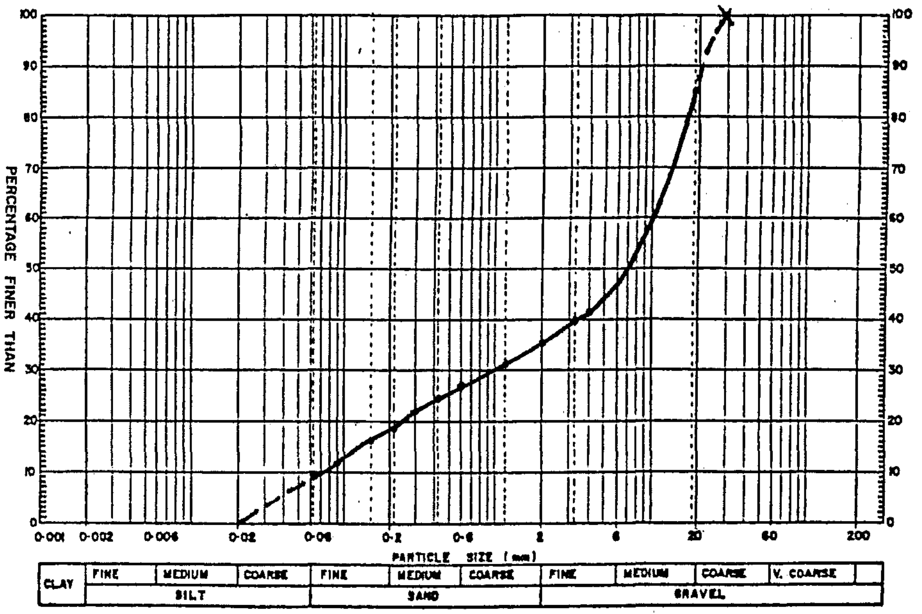


SAMPLE: O



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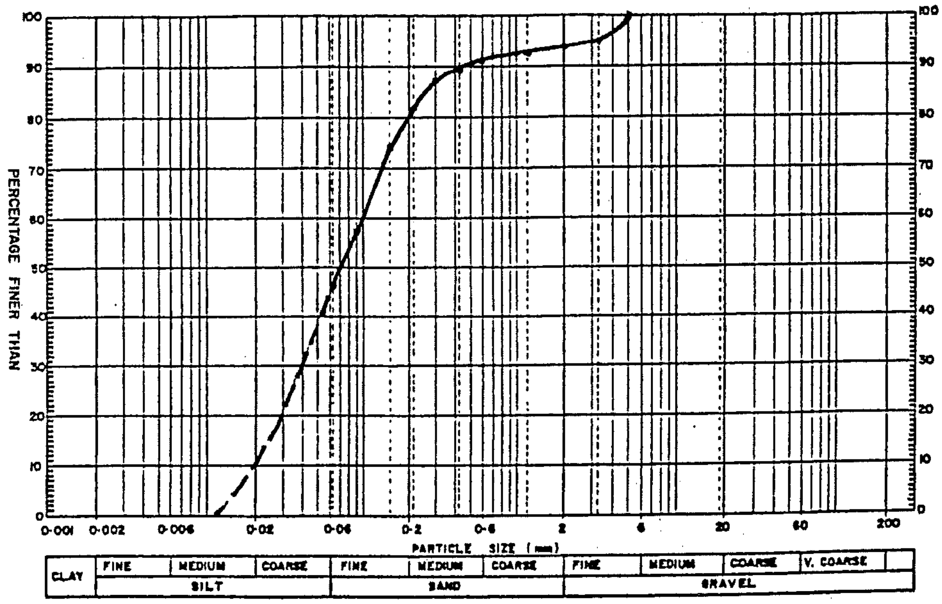
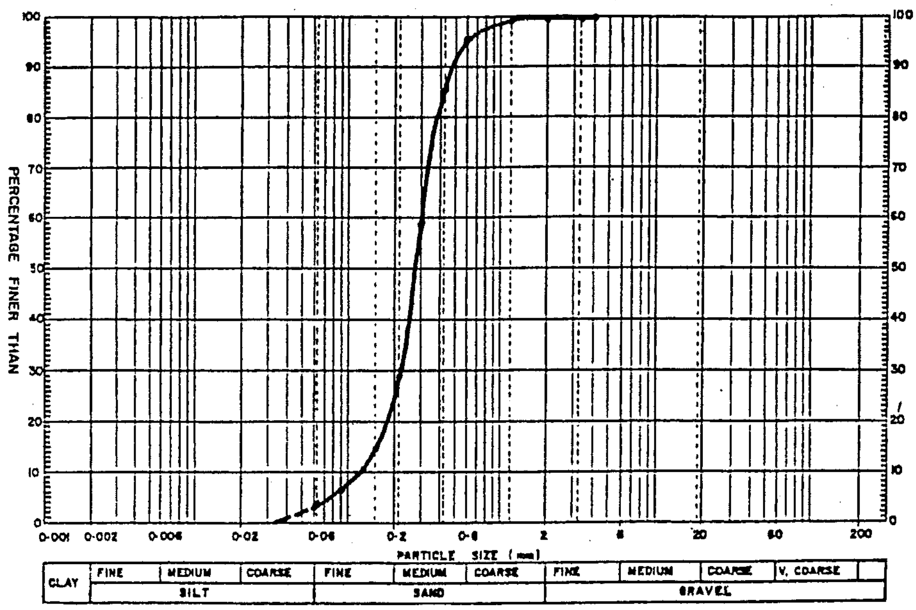
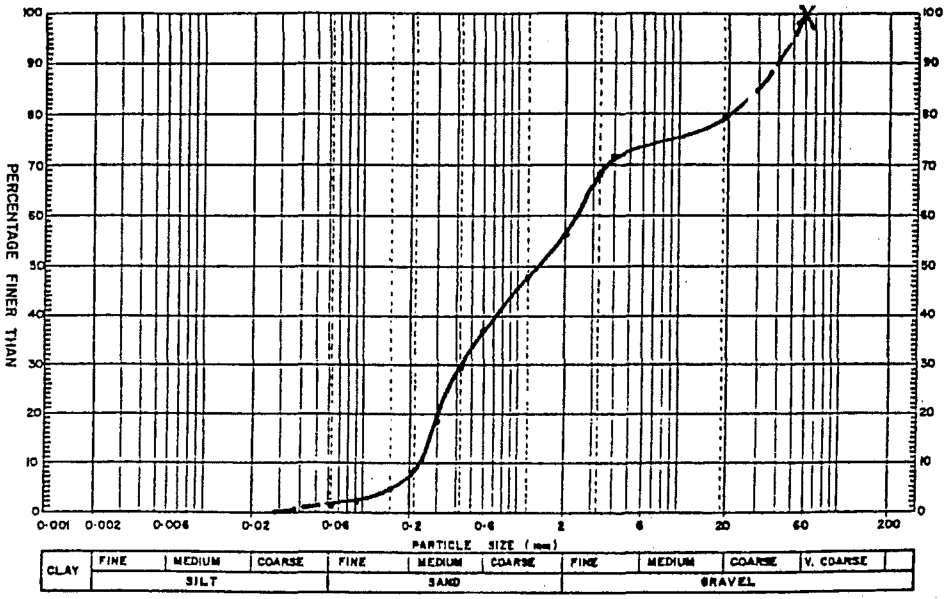


SAMPLE: Q



SAMPLE: R


PERCENTAGE FINER THAN
PARTICLE SIZE (mm)
0·001
0·002
0·006
0·02
0·06
0·2
0·6
2
6
20
60
200
CLAY
FINE
MEDIUM
COARSE
SILT
SAND
GRAVEL
V. COARSE

SAMPLE: S

APPENDIX E

DESCRIPTION OF THE MODIFIED MERCALLI SCALE

The Modified Mercalli Scale of earthquake intensity

Intensity	Description of characteristic effects	Maximum acceleration of the ground	Magnitude corresponding to highest intensity reached
MM I	Instrumental: detected only by seismographs		
		10	
MM II	Feeble: noticed only by sensitive people		
		25	3.5
MM III	Slight: like the vibrations of a passing lorry; felt only by people at rest, especially on upper floors		to
		50	4.2
MM IV	Moderate: felt by people while walking; rocking of loose objects, including standing vehicles		4.3
		100	to
MM V	Rather Strong: felt generally; most sleepers are awakened and bells ring		4.8
		250	
MM VI	Strong: trees sway and all suspended objects swing; damage by overturning and falling of loose objects		4.9 - 5.4
		500	
MM VII	Very Strong: general alarm; walls crack; plaster falls		5.5 - 6.1
		1000	
MM VIII	Destructive: car drivers seriously disturbed; masonry fissured; chimneys fall; poorly constructed buildings damaged		6.2
		2500	to
MM IX	Ruinous: some houses collapse where ground begins to crack, and pipes break open		6.9
		5000	
MM X	Diststrous: ground cracks badly; many buildings destroyed and railway lines bent; landslides on steep slopes		7.0 - 7.3
		7500	
MM XI	Very Distastrous: few buildings remain standing; all services out of action; great landslides and floods		7.4 - 8.1
		9800	
MM XII	Catastrophic: total destruction; objects thrown into air; ground rises and falls in waves		> 8.1 (maximum known 8.9)